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THE GRANITIC SEQUENCE IN THE SOUTHERN COMPLEX OF UPPER MICHIGAN

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ERRATA

Systematic Packing of Spheres

By L. C. GRATON and H. J. FRASER

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(Please attach to page 785)

Page	
800	In Case 3 of Fig. 5 the angle at the right far corner of the drawing should be "60°" instead of "90°" as shown.
817	Line 7 — Read "from" instead of "form". Line 22 — Read "is" instead of "are" and change dash to comma.
843	Line 12 — Read "823" instead of "824".
873	Last line of Col *VI* of table, read "1056.43" instead of "1572.01" and last line of Col. *VIII* read "577.32" instead of "675.46".
875	Line 17 — Read "3.67" instead of "6.89". Line 18 — Read "6.28" instead of "12.65".
877	Line 22 — Read "somewhat" instead of "considerably".
892	Line 7 of footnote 62 — Omit "half of".
896	Line 5 below quotation in fine print — Read "60-degree" instead of "60 per cent".
906	Sixth line of footnote 66 — Read "constriction" instead of "construction".

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ABSTRACT

Granites representing three distinct periods of pre-Cambrian intrusion are recognized in the Southern Complex of the Upper Peninsula of Michigan. Two of these are believed to be Archean, and one post-Huronian. Descriptions of the granites and the methods employed for dating them are presented. The Southern Complex is made up dominantly of Archean rocks, and is not, as some investigators have stated, composed for the most part of post-Huronian granite.

INTRODUCTION

South of the Marquette synclinorium, in the Upper Peninsula of Michigan, lies the Southern Complex, an area of pre-Cambrian igneous and metamorphic rocks which has been a subject of controversy since 1851. In that year Foster and Whitney[1] published a statement implying that the granite south of the Marquette trough is intrusive into what are now regarded as Huronian rocks. During the ensuing decades the literature referring to the area has contained numerous age postulates for the granitic rocks, different investigators having variously regarded these as Archean, Archean and post-Huronian, post-Huronian, and post-Cambrian. The arguments from 1851 to 1897 were summarized by Van Hise, Bayley, and Smyth,[2] and were

[1] J. W. Foster and J. D. Whitney, "Report on the Geology and Topography of the Lake Superior Land District: Part II, The Iron Region, together with the General Geology," *32nd Congress, Spec. Sess., Senate Doc.*, Vol. III, No. 4 (1851).

[2] C. R. Van Hise, W. S. Bayley, and H. L. Smyth, "The Marquette Iron-bearing District," *U.S. Geol. Surv. Mono. 28* (1897), pp. 1–148.

detailed to 1909 by Van Hise and Leith,[3] who concluded that granites of two ages are present in the Marquette district, one Archean and the other post-Huronian. For twenty-four years their statement on the subject was apparently regarded as satisfactory by geologists.

The stimulus for the present investigation was provided by a recent series of three articles by Lamey,[4] the purport of which is that the entire area of the Southern Complex is made up, with possible minor exceptions, of post-Huronian granite. He recorded no evidences of more than one period of granitic intrusion. Because of the emphasis given by Lamey's work to the wide divergence in the views of various geologists who have studied the complex, it was thought advisable to attempt to reconcile the apparently contradictory facts available on the subject, and to unravel the sequence of granitic intrusions in the area with such exactness as is made possible by the field evidence. In geologic work in this district it is possible to apply ordinary stratigraphic methods only as far down in the geologic column as the base of the Lower Huronian. Within the Southern Complex proper such methods cannot be employed, but it is believed that in this paper the complexities developed through the several periods of igneous intrusion have been reduced to a semblance of order.

The field work in connection with the problem was done by the writer during July and August of 1934 and September of 1935.

The writer is indebted to Dr. Andrew Leith of the University of Wisconsin for suggesting the problem and for valuable aid in the course of the investigation. Mr. B. W. Meek, also of the Department of Geology of the University of Wisconsin, acted as assistant during a portion of the field work.

NATURE OF THE AREA

The Southern Complex is located between latitudes 45°54′ N. and 46°30′ N., and longitudes 87°18′ W. and 88°6′ W., roughly.

[3] C. R. Van Hise and C. K. Leith, "Pre-Cambrian Geology of North America," *U.S. Geol. Surv. Bull. 360* (1909), p. 140.

[4] C. A. Lamey, "Granite Intrusions in the Huronian Formations of Northern Michigan," *Jour. Geol.*, Vol. XXXIX (1931), pp. 288–95; "The Intrusive Relations of the Republic Granite," *ibid.*, Vol. XLI (1933), pp. 487–500; "Some Metamorphic Effects of the Republic Granite," *ibid.*, Vol. XLII (1934), pp. 248–63.

It is for the most part readily accessible, inasmuch as good roads occur in close proximity to it on all sides and the interior is traversed by numerous trails.

In outline the complex is rudely circular, and is bounded on the north, west, and south by folded Huronian deposits and on the east by Paleozoic sediments. Folded Huronian strata occur in such prominent structural features as the Marquette trough, the Sturgeon River tongue, the Turner tongue, and the Felch syncline. The Republic trough, a narrow syncline with a northwesterly trending axis, extends a short distance into the northwest part of the granite area, and is probably an extension of the Marquette folding.

So far as is known, the whole of the interior portion is made up of granite, schists, and gneisses, with numerous, though local, intrusions of greenstones and basic igneous material, notably diorites and diabases. The igneous rocks are usually separated from the Huronian deposits by erosional valleys, and visible contacts are few.

Much of the interior is overlain by flat, monotonous sand plains, studded with pine groves and bearing small lakes and swamps in numerous shallow depressions. Outcrops in these areas are few and widely scattered. Toward the margins of the district the topography becomes somewhat more rugged, assuming an aspect typical of glaciated pre-Cambrian areas; knob-like hills are common, with rock exposures on their summits and flanks, and are separated by swampy or drift-covered areas. Many of the granite outcrops exhibit marked glacial polishing and *roche moutonnée* development, with glacial striae rather abundant.

The Huronian deposits have been complexly folded and metamorphosed. They consist mainly of quartzites, graywackes, slates, iron formation, schists, and, less abundantly, dolomites and volcanics. Where present in the area they show evidences of pronounced metamorphism, of both dynamic and contact varieties. In several localities they have been intruded by granite dikes. Intrusions of greenstones into the Huronian are abundant, taking the forms of dikes and sills. Pegmatites are likewise common, but are confined largely to the granite area proper.

The areal distribution of the various rock types and their postulated ages are indicated in general on the accompanying map (Fig. 1).

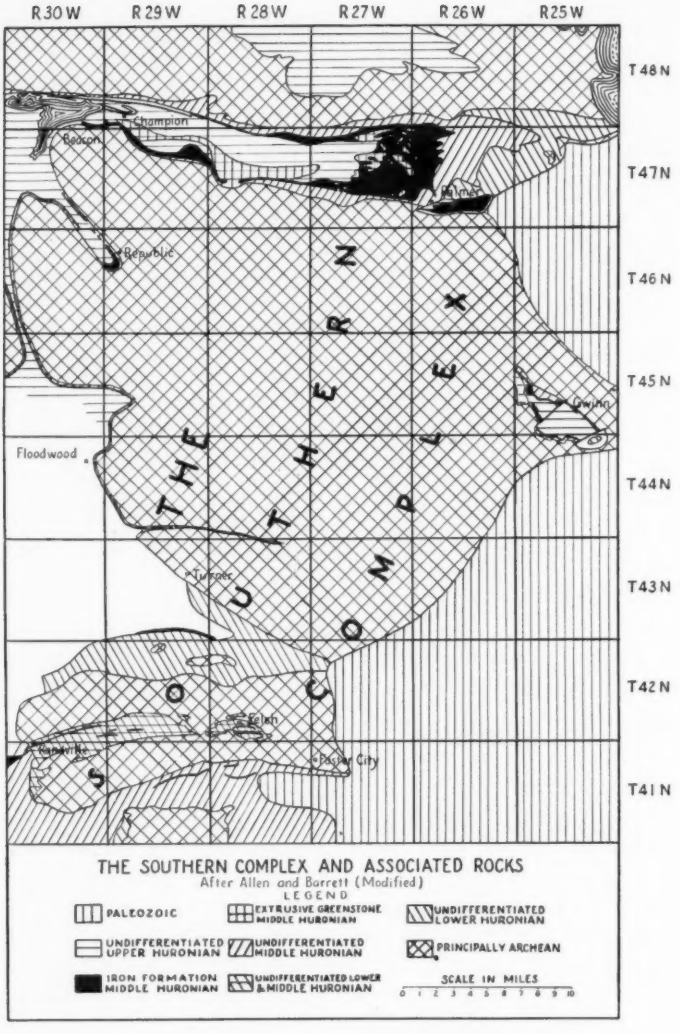

FIG. 1.—The Southern Complex and associated rocks

The periods of granitic intrusion recognized by the writer in the Southern Complex, and their relations to the various ages of rocks with which they are associated, are shown in Table I.

As a broad generalization, it may be stated that the major portion of the interior of the complex is occupied by the Laurentian granite-porphyry, and that occurrences of the Keewatin-type schists,

TABLE I

AGE RELATIONS OF THE ROCKS OF THE SOUTHERN COMPLEX

Era		Period	Formation
Paleozoic		Cambrian	
		Lipalian Interval	
Pre-Cambrian	Algonkian	Keweenawan	Killarney granite
		Huronian	Upper
			Middle
			Lower
		Eparchean Interval	
	Archean	Laurentian	Granite-porphyry Granite of the Archean injection gneiss
		Keewatin	Schists

the Archean injection gneiss, and the Killarney granite are ordinarily located most abundantly near the contacts of this porphyry with the folded Huronian deposits of the area. The Killarney granite, in addition to cutting the pre-Huronian rocks, is found to intrude the Huronian in numerous instances.

THE KEEWATIN-TYPE SCHISTS

The oldest rocks in the Southern Complex are the Keewatin-type schists. These consist in a general way of micaceous schists, hornblendic schists, and a variety gradational between these two, the micaceous amphibole-schists. They are found in many places throughout the district, but are most abundant near the contacts of the folded Huronian beds with the granites of the complex, and have been variously intruded by all the granites recognized by the writer. The relations of these schists to the Huronian are generally clear, and are demonstrated by visible contacts or, not uncommon-

ly, conglomerates in the Huronian rocks bearing recognizable pebbles of the schists. The evidence establishes definitely that the so-called Keewatin-type schists are pre-Huronian in age, and, with contrary evidence lacking, all are placed in the Archean. Although proof has not been found, the possibility that some of these schists are the highly metamorphosed remnants of Knife Lake sediments is not to be neglected.

The occurrrence of the Keewatin-type schists in greatest abundance near the contacts of the folded Huronian with the Laurentian granite-porphyry suggests that these schists were not entirely removed by the erosion of the Laurentian mountain range, the development of which was associated with the intrusion of the granite found in the Archean injection gneiss. Nor were they obliterated by the presumable erosional truncation of the later Laurentian mountains, to the formation of which the intrusion of the Laurentian granite-porphyry was related. A plausible explanation of their persistence through periods of Archean erosion is that they were roof pendants in the Laurentian batholiths and so were locally preserved during the bevelling of these granite masses. The schistose, bevelled roof pendants were, during the Killarney orogeny, folded with the Huronian strata, and are now found closely associated areally with the Huronian structures. The Huronian rocks and the nearby Keewatin-type schists occupy low points in the basement rocks, and so have not been completely removed by erosion subsequent to the Killarney deformation.

The Keewatin-type schists typically occur as fragments or masses of varying sizes caught up in and intruded by the three granites distinguished by the writer. In some instances they are locally much more abundant than the granites intruding them, as is the case in much of that part of the Southern Complex immediately south of the Marquette synclinorium. Portions of the Palmer gneiss are probably Keewatin, although much of this consists of sheared and intruded Huronian rocks, as Van Hise and Leith[5] believed and Lamey[6] has recently proved. The great masses of schists south of the Palmer gneiss must, in the absence of contrary evidence, be re-

[5] *Op. cit.*, p. 333.

[6] "The Palmer Gneiss," *Geol. Soc. Amer. Bull. 46* (1935), pp. 1137–62.

garded as Keewatin. Similarly, south of the western end of the Marquette trough intimately intruded Keewatin-type schists are very abundant.

The original nature of the rocks from which the Keewatin-type schists have been derived is obscure because of the intense metamorphism which they have undergone. Probably many of them were basic flows and others were possibly composed of clastic materials. It is also possible that they represent metamorphosed rocks of several different ages, but this cannot be readily demonstrated.

THE ARCHEAN INJECTION GNEISS

In the southern part of the Southern Complex are occurrences of injection gneiss formed by the intimate intrusion of the Keewatin-type schists by a medium-grained gray to pink granite consisting of quartz, orthoclase, oligoclase, and biotite, with small amounts of zircon, apatite, titanite, magnetite, and chlorite. Although there can be little doubt that this intrusion was originally widespread in the area, the granite is at present preserved as the intrusive material in well-banded injection gneiss in only a few outcrops, notably at Randville (SE. $\frac{1}{4}$ of Section 33, T. 42 N., R. 30 W.), north of Felch (NE. $\frac{1}{4}$ of Section 29, T. 42 N., R. 28 W.), and west of Turner (NE. $\frac{1}{4}$ of Section 9, and the NE. $\frac{1}{4}$ and NW. $\frac{1}{4}$ of Section 10, T. 43 N., R. 29 W.).

The only known occurrences of the Archean injection gneiss are found near the contacts of the igneous rocks of the complex with the folded Huronian deposits, probably for the same reason that a large proportion of the Keewatin-type schists are so located. The gneiss has been developed through the intimate intrusion of Keewatin-type schists, generally along cleavage planes, by granite. The intimacy of intrusion seems to show an original highly fluid condition of the intrusive material; wavy crenulations and irregular, unoriented drag folds in the schistosity point to a softening of the schists at the time of injection.

Observed relations to the later Laurentian granite-porphyry mark this granite as a definite type and establish it as Laurentian and the oldest granite in the district. It is possible that the injecting granites in the three exposures mentioned may not be of the same age, but

there is no evidence available to make it imperative that they be separated as to time of intrusion. The gneiss formed by the injection of this Laurentian granite into the Keewatin-type schists is referred to as the Archean injection gneiss.

It should perhaps be stated here that the term "Laurentian" is applied to all granites which intrude the Keewatin-type schists and are pre-Algonkian. It is understood that this term may include granites of different ages, within the stated limits.

THE LAURENTIAN GRANITE-PORPHYRY

The second period of granitic intrusion in the Southern Complex is represented by granite-porphyry, which, although outcrops are absent in much of the district, is thought to be the dominant rock type areally. At Turner (NE. $\frac{1}{4}$ of Section 9 and the NW. $\frac{1}{4}$ of Section 10, T. 43 N., R. 29 W.) it intrudes the Archean injection gneiss and so is younger than that rock type. It is not found in contact with the Archean gneiss at Randville or north of Felch; consequently the correlation of these exposures with the Turner gneiss is necessarily primarily based upon lithology, but is believed to be warranted. The porphyry in many places intrudes the Keewatin-type schists, and is definitely younger than these. Characteristically it is pink to gray in color, and where not deformed subsequent to its emplacement bears large phenocrysts of orthoclase, microcline, and microperthite, in a groundmass of quartz and biotite, with lesser amounts of oligoclase, apatite, zircon, and muscovite. The principal variations in its lithology over the area are merely those of color and of differences in content of femic minerals, these being locally abundant in the rock near contacts with intruded Keewatin-type schists. The phenocrysts attain a major dimension of as much as 2 inches, are commonly twinned according to the Carlsbad law, and are usually alined in a parallel fashion, probably by primary flowage of the granite while in a viscous condition. There is nothing in the area to indicate more than a single period of porphyry intrusion.

Three lines of evidence demonstrate the pre-Huronian age of the granite-porphyry. These are: (1) lack of intrusion of the Huronian by the granite-porphyry; (2) evidence of deformation and shearing of the porphyry after its complete solidification; (3) basal conglom-

erates in the Huronian containing boulders of previously sheared granite-porphyry, and in erosional contact with this granite. This order is maintained in the following discussion of these points.

First, nowhere in the entire area is the granite-porphyry found to intrude the Huronian. The only intrusive relationships which it exhibits are with the Keewatin-type schists and the Archean injection gneiss. It would be strange, indeed, if the intrusion of this great mass of igneous material in post-Huronian time were unaccompanied by dikes and offshoots of considerable magnitude in the Huronian rocks. In this connection, the continuity of the relatively thin Middle Huronian Negaunee iron formation along the north and northwestern margins of the Southern Complex is pointed out. It would seem that if the granite-porphyry were post-Negaunee the iron formation would be transgressed by this rock at many places.

Second, near the present contacts with the Huronian rocks of the Republic trough, the Turner tongue, the Sturgeon River tongue, and the Felch syncline, the porphyry shows mylonitization, shearing, and slicing of the feldspars and the quartz, with a resulting mechanical elongation or foliation of the mineral constituents which now parallels in a broad way the axes of folding of the Huronian strata, and which becomes increasingly marked as the contacts with the Huronian are approached. This condition is not found in that part of the district immediately south of the Marquette synclinorium; the possible reasons for this are given separate consideration elsewhere in this paper. The deformation of the porphyry cannot be ascribed to primary flowage while in a viscous state, but is thought to be due to mashing and shearing subsequent to its complete solidification. For example, the mashed granite-porphyry is cut by schistose basic dikes whose schistosity is parallel in strike and dip to the foliation directions in the deformed porphyry. The time interval elapsing between the emplacement of the granite-porphyry and its deformation must therefore have been sufficiently great to permit solidification and fracturing of the porphyry, intrusion of the basic dikes, and solidification of the material which they contain. This sequence was evidently complete before the rocks were deformed. Eventually, both porphyry and basic dikes were mashed, apparently through being involved in folding on a rela-

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tively large scale. Further, the quartz, as well as the feldspar phenocrysts, of the porphyry exhibits marked cataclasis where the rock shows evidences of deformation. This would not be the case if the rock was deformed while in a viscous condition, inasmuch as in this state the quartz would doubtless have been liquid.

The evidence is, then, that the porphyry was deformed subsequent to its complete solidification. This deformation, which is very evident in the porphyry because of the original large size of the phenocrysts, is likewise found in the granite of the Archean injection gneiss. In this rock, however, it is not so noticeable because the injecting granite is one of medium grain, and the granulation it has undergone is not at once apparent. Under the microscope the cataclasis of the feldspars and quartz is readily visible.

The deformation of the granite-porphyry may have been brought about by the same forces which produced the folding of the Huronian rocks of the area, in post-Huronian, pre-Cambrian time; it may be due to still earlier diastrophism; or it may be the result of several periods of orogeny. In any case, it is sufficient to establish the age of the porphyry as pre-Huronian. Obviously this rock could not have been emplaced subsequent to the latest orogeny in the area, in post-Huronian time, inasmuch as it is deformed. Nor could it have accompanied the post-Huronian orogenic disturbance, because it has been shown that the deforming forces which affected it acted on a completely solidified porphyry mass; therefore a very considerable time interval elapsed between its emplacement and its deformation. Regarding the possibility of its being of Huronian age (which presupposes that it was mashed only by those forces which folded the Huronian rocks of the area during the post-Huronian), no evidence exists of the intrusion of a large granite batholith in Huronian time in this district. The intrusion of such a batholith would have caused intense deformation of the invaded Huronian rocks. These would, then, necessarily be discordant with Huronian beds deposited after the emplacement of this porphyry magma. The Huronian strata of the area are, however, remarkably concordant in strike and dip in any single major structural unit, and show evidences of only one principal period of deformation, the post-Huronian. On the

basis of these considerations alone, therefore, the granite-porphyry is neither post-Huronian nor Huronian in age.

Third, convincing evidence of the pre-Huronian age of the granite-porphyry and of at least a portion of the cataclasis which it exhibits is found in a basal conglomerate located at the southeastern end of the Republic trough, in the NW. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of Section 18, T. 46 N., R. 29 W., which was first described by Smyth[7] in 1893. On the steep northwest face of a large outcrop of the mashed granite-porphyry, a few hundred yards north of State Road 95 and adjacent to the Republic baseball grounds, is a plaster conglomerate consisting of slab-like boulders of mashed granite-porphyry, some possessing a maximum dimension of 5 feet, embedded in a schistose, chloritic, arkosic matrix, in which are contained likewise numerous rounded pebbles of black schist and vein quartz. This conglomerate lies at the base of the Middle Huronian Ajibik quartzite, and the contact between granite-porphyry and conglomerate is unquestionably erosional. The trend of the foliation in the basal deformed granite-porphyry is parallel to the strike of the axis of the Republic syncline, but the directions of foliation in the mashed porphyry boulders of the conglomerate are at varying angles to that of the granite-porphyry which underlies it. This shows that some part of the deformation of the porphyry was produced by pre-Huronian diastrophism. Apparently during the Killarney orogeny the compression of the conglomerate was taken up largely by the matrix, which was rendered schistose, resulting in only very slight deformation of the porphyry boulders.

Lamey[8] states that, in the Republic area,

> across the river, in the line of strike, the iron formation and quartzite are missing, and in their place there appears a large hill of granite. Though there is no positive evidence that the granite has cut discordantly across the strike of the Negaunee iron-bearing formation, the field relations suggest very strongly that such is the case.

The granite hill in question is composed of mashed granite-porphyry identical with that underlying the basal conglomerate just described,

[7] H. L. Smyth, "A Contact between the Lower Huronian and the Underlying Granite in the Republic Trough, near Republic, Michigan," *Jour. Geol.*, Vol. I (1893), pp. 268–74

[8] "The Intrusive Relations of the Republic Granite," *loc. cit.*, p. 493.

and is located only a short distance northwest of this conglomerate. Evidently, then, the absence of the Ajibik quartzite and Negaunee iron formation along the southwest margin of the Republic trough is due to erosion, since the Huronian of this part of the area lies unconformably upon the Laurentian granite-porphyry. Any suspicions that the missing formations are lacking because of intrusion and assimilation by the granite-porphyry are therefore groundless.

Other evidence, in addition to the Republic conglomerate, that the granite-porphyry has undergone more than one period of deformation is found in the NE. $\frac{1}{4}$ of Section 26, T. 47 N., R. 29 W., where two outcrops of the porphyry occur, spaced approximately 50 feet apart in a NW.–SE. direction. The northwesterly exposure contains two well-developed shear zones, each about 3 feet wide, in which the porphyry is so mashed as to be almost truly schistose. The older of these shear zones strikes N. 45° W. and the younger N. 85° W., obliterating that earlier formed where the two zones intersect. In the southeasterly outcrop are also two shear zones, almost identical in appearance and width with those in the other exposure. The older of these strikes N. 5° E. and the younger N. 45° E., replacing the N. 5° E. direction of shear where the two zones cross. The porphyry here is undeformed away from the shear zones, and possesses a primary feldspar alinement striking variously from N. 85° W. to N. 65° W. These evidences of shearing might possibly be regarded as having developed during four distinct periods of deformation. The writer is inclined to suspect that there are only two periods of shearing involved and that the two outcrops are separated by a fault along which displacement has occurred in such a manner as to produce four divergent strikes of the shear zones where only two originally existed.

Another exposure of Huronian conglomerate demonstrating the pre-Huronian age of the granite-porphyry is located in the NW. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of Section 7, T. 42 N., R. 28 W., and is associated with the easternmost of the two small areas of granite-porphyry surrounded by the Huronian rocks of the Sturgeon River tongue. The conglomerate mantles portions of the south slope of a small granite hill a short distance east of the East Branch of the Sturgeon River. The granite-porphyry here is typically mashed, bearing a rude folia-

tion which strikes east-west. It contains local pink to red, fine-grained phases. The conglomerate is thoroughly mashed and sheared, and is made up of small, elongated pebbles with a maximum diameter of approximately $1\frac{1}{2}$ inches, embedded in an arkosic, chloritic matrix. The pebbles appear to be composed for the most part of the red, fine-grained portions of the underlying granite-porphyry. This conglomerate apparently represents the base of the Lower Huronian rocks of the Sturgeon River tongue, and there can be no reasonable doubt as to the erosional relationships existing between it and the granite-porphyry. The occurrence was originally described by Bayley,[9] in 1899.

The undeformed porphyry, exhibiting primary flowage alinement of the phenocrysts, occurs in the interior of the complex. The sheared, mashed, granulated equivalent is found near the contacts with the Huronian structures, and has been recognized by almost all investigators. Regardless of whether the diastrophism responsible for the mashing of the porphyry was post- or pre-Huronian, or whether the observed mashing is the cumulative effect of several periods of folding, the evidence demonstrates conclusively that the granite-porphyry was emplaced in the pre-Huronian, and is neither Huronian nor post-Huronian in age. Accordingly, it belongs in the Archean, and is regarded as Laurentian.

The phenomenon of the mashing of the granite-porphyry near the Huronian contacts can be observed readily in the vicinity of the Felch syncline, the Sturgeon River tongue, the Turner tongue, and the Republic trough, all consisting of folded Huronian strata. Series of outcrops which demonstrate it are so numerous that it would be futile to attempt a complete enumeration. A striking and readily accessible example illustrating the differences between deformed and undeformed porphyry, as well as one which affords evidence that the mashing occurred subsequent to the complete solidification of the granite, is found in two outcrops located along the railroad right-of-way approximately $1\frac{1}{4}$ miles north of Randville, in the SE. $\frac{1}{4}$ of the NE. $\frac{1}{4}$ of Section 28, T. 42 N., R. 30 W. These outcrops are spaced 375 yards apart in a north-south direction. The northernmost

[9] J. M. Clements, H. L. Smyth, and W. S. Bayley, "The Crystal Falls Iron-bearing District of Michigan," *U.S. Geol. Surv. Mono. 36* (1899), p. 462.

occurrence shows the undeformed granite-porphyry possessing primary feldspar alinement striking N. 80° E., with no dip discernible. The feldspars evince no traces of mashing and granulation. One large, massive, unsheared basic dike intrudes the porphyry.

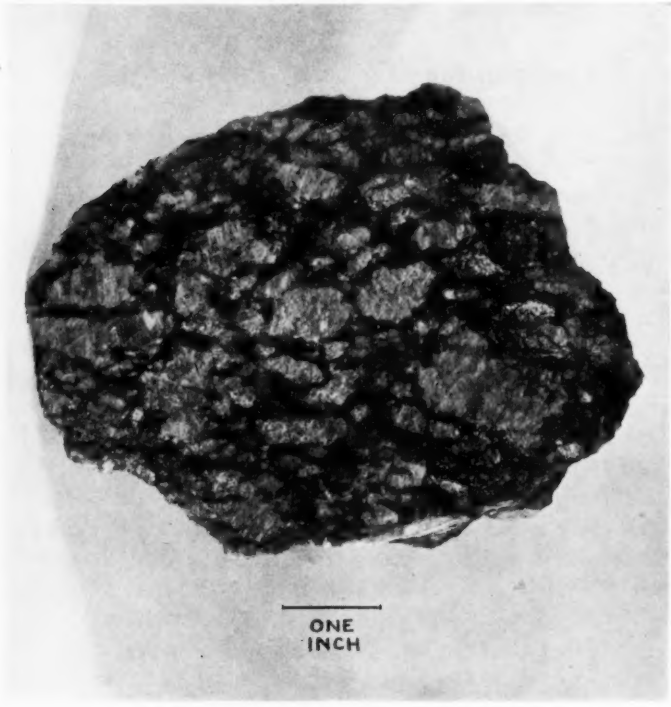

FIG. 2.—The undeformed Laurentian granite-porphyry

In the southernmost outcrop the phenocrysts in the granite-porphyry are noticeably mashed, the resulting rude foliation striking east-west and dipping 75° S. The granite in this outcrop is cut by four basic dikes, three of which are from 1 to 3 feet in width, and the fourth 15 feet wide as exposed. The three narrow dikes are markedly schistose, their cleavage paralleling the direction of mashing of the

phenocrysts in the porphyry. The larger dike is massive in the center, but is schistose at and near its contacts with the granite which it intrudes. Evidently the effects of deformation disappear at some point between these two outcrops.

Figures 2 and 3 illustrate the differences between the undeformed granite-porphyry and its mashed equivalent near the contacts with Huronian.

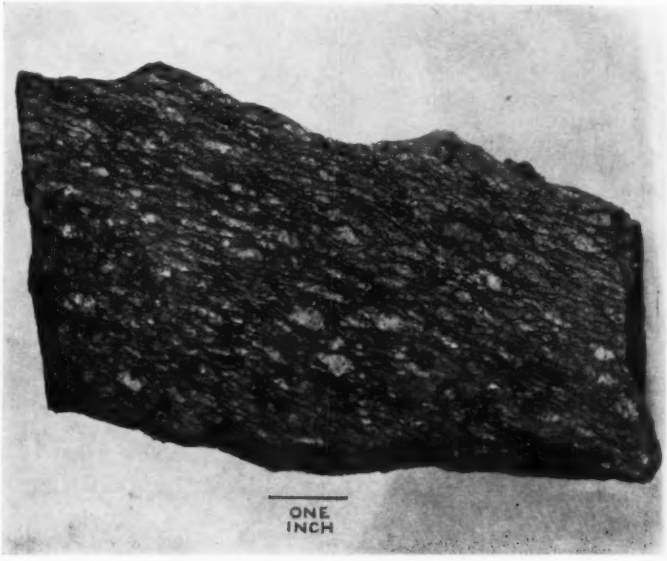

FIG. 3.—The deformed Laurentian granite-porphyry

In that portion of the Southern Complex which lies immediately south of the Marquette synclinorium, the deformation of the granite-porphyry is not generally apparent. Several explanations for the absence of this phenomenon are possible. Along the south margin of the eastern part of the Marquette trough is a considerable thickness of Palmer gneiss and Keewatin-type schists. South of these is found the undeformed porphyry. It is probable that, during the folding of the Huronian strata, the shear involved in the

differential movement between the Huronian and the basement rocks was taken up by the Palmer gneiss and Keewatin-type schists lying between the Huronian and the granite-porphyry. Any compression of the basement which might have taken place during this folding must have affected only the Keewatin-type schists located relatively near the Huronian contacts, and did not extend as far south as the points where the porphyry becomes quantitatively important.

Along the southern margin of the western portion of the Marquette synclinorium, in positions where normally the sheared, mashed porphyry would be expected to occur, is found medium-grained gray to pink granite, locally pegmatitic, showing no evidences of deformation, and large amounts of injection gneiss formed by the intimate intrusion of this granitic material into basic schists. The granite is not dissimilar in general appearance and lithology to the Killarney granite in other parts of the Southern Complex, and may be regarded as its equivalent, in view of the contact metamorphism of the Huronian in the western portion of the Marquette trough and the apparent assimilation of the Ajibik quartzite south of Beacon by this granite. It is present to the exclusion of the granite-porphyry. If the mashed granite-porphyry once existed in this portion of the district it has been engulfed by the Killarney granite, or, as the writer is not unwilling to suggest, the Killarney granite here represents refused Laurentian granite-porphyry. The concept of the development of the Killarney granite by this means has been favored by Swanson[10] and others. The injection gneisses here indicate, by complex crenulations of the schistose material, by wavy, distorted wisps of schist in the granite, and by the intimate character of intrusion, relatively high temperatures and a softened condition of the schists at the time of emplacement of the granite. It is not improbable that during the Killarney orogeny the pressures and temperatures associated with the Marquette folding were such that the basement granite-porphyry was locally refused, rather than being granulated and mashed.

Another possible explanation of the absence of mashing of the porphyry along the southern margin of the Marquette synclinorium is that the deformation of the basement which resulted in the com-

[10] C. O. Swanson, *Report on the Portion of the Marquette Range Covered by the Michigan Geological Survey in 1929* (Lansing: Mich. Geol. Surv., 1930), p. 15. Mimeographed.

pression and granulation of the granite-porphyry was not associated with the Killarney orogeny, but was due to earlier diastrophism. This implies that the general observed parallelism between the directions of foliation in the porphyry and the axes of folding in the other Huronian structures of the area is fortuitous, and that the coincidence of axes of folding between the Killarney and earlier orogenies did not extend to the Marquette trough.

THE KILLARNEY GRANITE

The third period of granitic intrusion in the Southern Complex is marked by the presence of red to pink granite with a broad textural range, varying from fine-grained to pegmatitic, which is observed in a number of instances to intrude the Huronian rocks, the Palmer gneiss, the Keewatin-type schists, and the Laurentian granite-porphyry. Although at present seen most abundantly near the contacts of the granite-porphyry with the Huronian, it may underlie much larger parts of the district than the observed areal distribution indicates. Much of the extensive contact metamorphism of the Huronian may be related to this intrusion. The characteristic color, lack of porphyritic texture, and absence of cataclasis or mashing produced by deformation subsequent to intrusion make it readily distinguishable from the Laurentian granite-porphyry. This red granite is known to intrude formations as young as the Upper Huronian Goodrich quartzite; further, the contact metamorphism of the Upper Huronian Michigamme slates, and numerous pegmatites and quartz veins in these, are presumably associated with the intrusion of this granite. It is not known to intrude the Cambrian rocks in the district. Consequently, it is regarded as Killarnean in age, and is thought to have been associated with the deformation which gave rise to the major folding of the Huronian strata. Its lack of cataclastic structures suggests that it was intruded subsequent to this period of folding.

Keweenawan sediments are lacking in the area; the term "Killarney" granite as here applied is loosely used to indicate granite of post-Huronian and pre-Cambrian age, in the absence of information which might enable it to be dated more accurately with respect to the Keweenawan. Moreover, it is by no means certain that all the granite exposures here considered to be Killarnean on the basis

of lithologic similarities and relations to the Huronian are post-Huronian. If dated strictly according to observed occurrences, the granite intrusives into the Huronian in separated portions of the district would necessarily be placed as post-Lower, post-Middle, or post-Upper Huronian, depending upon the age of the youngest rocks known to be invaded at any given locality. However, because it is believed that the Huronian rocks in this area experienced their major folding in post-Huronian time, and, reasonably, that the granite intrusives in the various Huronian beds were associated with this period of orogeny, all occurrences of granite within the Huronian are grouped as post-Huronian in age.

A number of instances of granite intruding the Huronian rocks associated with the Southern Complex have been described by Lamey,[11] and it seems unnecessary to recount these in this paper. The granite is usually found as dikes, stringers, and irregular masses, variously intruding the earlier rocks of the area. Its distribution is typically spotty and irregular, and no masses of great size or remarkable continuity were noted. Although it appears to be concentrated within the Huronian strata and near the contacts of the Laurentian granite-porphyry with the Huronian rocks, in the interior of the complex are occasionally found masses of granite similar to the Killarney type lithologically which cannot be dated with reference to the Huronian. This sporadic distribution may be due to local and limited refusion of the Laurentian granite-porphyry during the Killarney orogeny, giving rise to molten material which forced its way into or locally assimilated the overlying rocks, or it may be that the observed occurrences of the Killarney granite are merely manifestations of the existence of a great batholith which possibly underlies much of the Southern Complex.

As previously stated, the marked differences in lithology between the Killarney granite and the Laurentian granite-porphyry enable the field distinction of the two varieties to be readily made.

The field distinction of the Killarney granite from the granite of the Archean injection gneiss is not difficult. Specifically, in regard to the Archean gneiss, at Turner the intrusive contacts between the gneiss and the later Laurentian granite-porphyry can be seen, per-

[11] "Granite Intrusions in the Huronian Formations of Northern Michigan," *loc. cit.*; "The Intrusive Relations of the Republic Granite," *loc. cit.*

mitting no doubt as to the age relationships between the two Laurentian granites. North of Felch the pre-Huronian age of the injection gneiss is not open to question. There the gneiss is intruded by a mashed pegmatite dike, cutting schist and granite alike, with the direction of rude foliation in the pegmatite parallel to the general direction of schistosity in the gneiss. Following the same line of reasoning employed with reference to dating the granite-porphyry, the mechanical mashing of this pegmatite shows it to be pre-Huronian, and, since it is obviously younger than the gneiss which it transects, the granite of the gneiss must likewise be pre-Huronian. On a lithologic basis this pre-Huronian granite is correlated with that of the pre-porphyry injection gneiss at Turner, and likewise with the injection gneiss at Randville, although there is no other reason, as regards visible contacts with other granites or with the Huronian, for classing the Randville occurrence as Archean. In each case the granite of the gneisses exhibits, under the microscope, cataclasis and mashing.

A short distance southeast of the village of Felch, and $\frac{1}{4}$ mile south of the center of Section 33, T. 42 N., R. 28 W., is a small quarry in the Lower Huronian Randville dolomite. On the east face of this quarry are exposed three anticlines and three synclines, overturned to the south, trending generally east-west, and pitching east at an angle of approximately 40°. A thin bed of quartzite within the dolomite serves to indicate the structure. In one of the synclines is an occurrence of biotite-schist intimately intruded along cleavage planes by highly siliceous, feldspathic, unsheared igneous material, which has apparently been the cause of considerable contact metamorphism of the dolomite. A short distance to the east is another quarry, located in complexly faulted, feldspathic amphibole-schist. Between the two quarries is an area covered with rubble and soil, and barren of outcrops. The amphibole-schist is unquestionably intruded near the eastern end of the eastern quarry by mashed granite-porphyry, and there are several occurrences of foliated, highly siliceous, occasionally pegmatitic, igneous material within this schist.

Lamey[12] states, with reference to these quarries, that the dolomite "forms a closely-folded syncline striking slightly north of west and plunging southeast . . . . an amphibole schist . . . . extends west-

[12] "The Intrusive Relations of the Republic Granite," *loc. cit.*, pp. 490–91.

ward toward the dolomite and in some places it apparently overlies and is infolded with the dolomite." It is his belief that the structures in the dolomite quarry continue their eastward pitch across the covered area and beneath the amphibole schist of the eastern quarry, and that this schist overlies the folded Randville dolomite. If this were true, the mashed granite-prophyry which intrudes the amphibole-schist, being of course younger than that schist, would be intrusive into the Huronian rocks. The determination of the correct age of this porphyry is of great importance, inasmuch as it is identical with the deformed granite-porphyry of other portions of the Southern Complex. If it could be shown to be post-Huronian in this locality, the assignment of the granite-porphyry of the remainder of the complex to the Laurentian would reasonably be incorrect.

It is the writer's contention that the amphibole-schist in the eastern quarry is not Huronian, but Keewatin in age, and that the mashed granite-porphyry intruding it is Laurentian rather than post-Huronian. This implies that the structures in the dolomite of the western quarry do not continue to pitch to the east across the covered area, but are cut off from the amphibole-schist by a fault of considerable magnitude. In such an event, the eastern quarry would be located on the upthrown side of the fault and the western quarry on the downthrown side. Further, the siliceous material intruding the biotite-schist which unquestionably overlies the Randville dolomite in the western quarry is thought to be Killarney, and not associated as to origin with the granite-porphyry to the east.

Corroboration of this concept is readily found. The accompanying detailed map (Fig. 4) of the two quarries reveals some important features which are not readily apparent upon casual examination of the area. The structural trends in the two quarries are obviously entirely discordant. The faulting in the amphibole-schist in the eastern quarry and lack of such faulting in the Randville dolomite of the western quarry suggest that the schist has had a much more complex orogenic history than the dolomite. It would be indeed remarkable if the deformation by faulting were to die out abruptly within the short distance separating the two quarries. The granite-porphyry is mashed, with the resulting foliation trending as indicated on the map. This demonstrates that both the granite-porphyry and the amphibole-schist have experienced at least one period

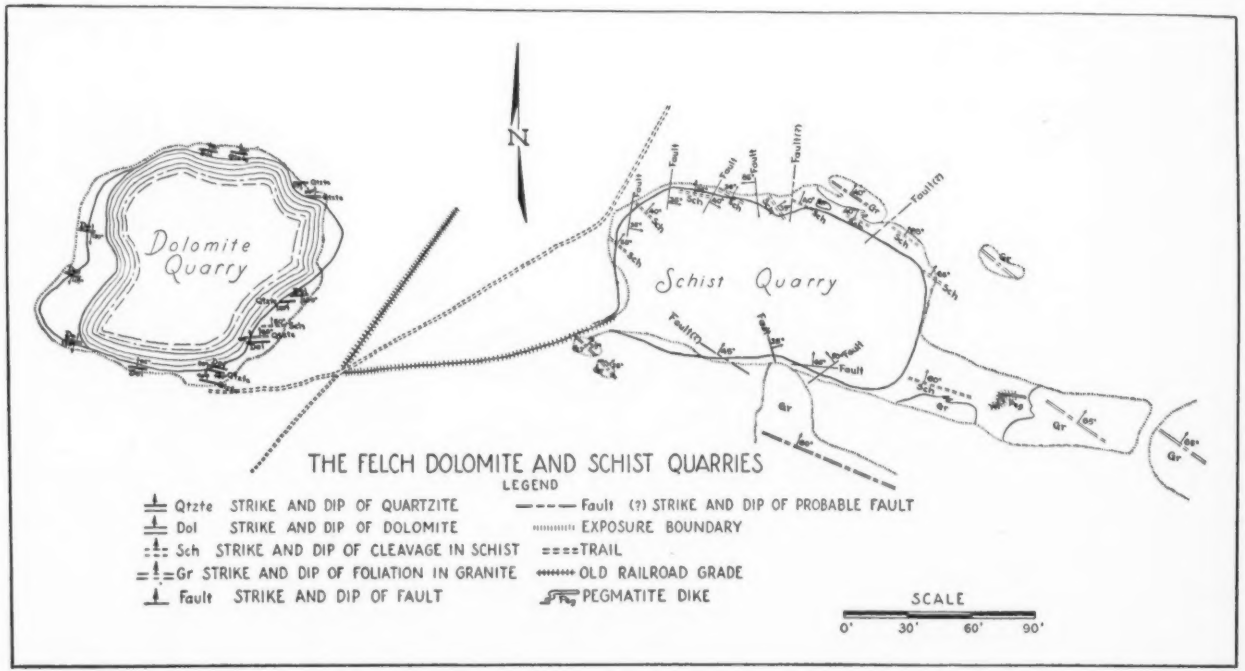

FIG. 4.—The Felch dolomite and schist quarries

of folding. Further, a small pegmatite stringer, evidently an offshoot of the mashed granite-porphyry, intrudes the amphibole-schist near the porphyry and its intrusion has notably deformed the schistosity. Obviously the cleavage in the schist existed prior to the intrusion of this stringer. The schist, then, has undergone folding preceding and following the emplacement of the granite-porphyry, and so is definitely placed as pre-Huronian, inasmuch as the Huronian rocks have been subjected to only one major orogenic disturbance. The mashing of the granite porphyry east of the schist quarry establishes it as Laurentian, employing reasoning similar to that used in dating this rock elsewhere in the Southern Complex.

Consequently, the two quarries are located in rocks of vastly different ages, brought into close proximity by a major fault which probably trends generally north-south. In the western quarry are the Lower Huronian Randville dolomite overlain by a small amount of post-Randville biotite-schist, and intrusive material of Killarney age. In the eastern quarry are Keewatin schist and mashed Laurentian granite-porphyry.

Lamey[13] has pointed out the assimilation of the Middle Huronian Ajibik quartzite by granite a short distance southeast of Beacon. There seems to be little doubt that this has occurred. It is important, however, to note that the assimilating granite is not the granite-porphyry, but is similar in appearance to occurrences of known Killarney granite elsewhere in the Southern Complex. Much of the schistose material in the intruding granite, which Lamey appears to believe has developed from impure phases of the intruded quartzite, may be Keewatin in age. No valid criteria appear to be available which might enable a distinction to be made in this highly complex district between Keewatin schists and schists developed through the metamorphism of possible slaty phases of the Ajibik quartzite.

Striking and readily accessible occurrences of the pink to red Killarney granite intruding the Palmer gneiss can be seen a short distance south of Palmer. This locality is given particular mention because this granite is here developed on a broader areal scale than in any other observed part of the Southern Complex. For a sum-

[13] *Ibid.*, p. 496.

mary of interesting examples of the Killarney granite intruding the Huronian rocks, the reader is referred to papers by Lamey previously mentioned.

MISCELLANEOUS EVIDENCES OF IGNEOUS ACTIVITY

The fifth group of rocks distinguished in the Southern Complex is composed of aplite dikes, quartz veins, pegmatites, and basic intrusives, of various ages. In general they do not bear directly upon the problem of the granitic sequence, and so are not given full consideration here. Specifically, many of the pegmatites and basic intrusives can be roughly dated in the same manner as the granite-porphyry. Sheared or mashed pegmatites may be referred to the pre-Huronian. Those of this variety which intrude the Archean injection gneiss may be connected genetically with either the granite of this gneiss or with the Laurentian granite-porphyry. Mashed pegmatites cutting the granite-porphyry are probably complementary to this period of intrusion. Unsheared pegmatites found in the Huronian deposits, in the Archean injection gneiss, or in the deformed Laurentian granite-porphyry may be reasonably regarded as after-effects of the Killarney intrusion. Unsheared pegmatite dikes found within the undeformed granite-porphyry may be Killarney in age, or they may be associated with the porphyry in origin. In the latter case they would evince no traces of shearing or mashing because of their being sufficiently far removed from loci of folding to have escaped deformation.

Where occurrences of basic intrusives are found to be sheared or schistose, it is probable that they were intruded prior to the folding of the Huronian rocks, but they may have undergone several periods of folding. Where massive, they may have been emplaced subsequent to the deformation of the Huronian strata, or they may have existed at a sufficient distance from the loci of folding to have been unaffected by deforming stresses.

SUMMARY

The Southern Complex is divided into five general groups of rock types, as follows:

1. The oldest rocks visible in the area are the Keewatin-type schists, which are classed as Archean.

2. These schists are intimately intruded in such a way as to produce injection gneisses by the next oldest rock type, a medium-grained gray to pink granite, of which only a few outcrops were observed. This granite is believed to be Laurentian, and therefore is a portion of the Archean complex of the district.

3. The second period of granitic intrusion in the area is represented by a gray to pink granite of a pronouncedly porphyritic character. This granite-porphyry is undoubtedly pre-Huronian in age, is considered to be Laurentian, and so is likewise a part of the Archean. It is the dominant rock type of the Southern Complex, and intrudes the Keewatin-type schists as well as the Archean injection gneisses formed by the intrusion of the earlier Laurentian granite into these schists. It is not known to intrude the Huronian.

4. The youngest granitic intrusion visible in the Southern Complex is a pink to red granite varying from fine-grained to pegmatitic in texture, and of relatively minor importance areally. It intrudes the Keewatin-type schists, the Laurentian granite-porphyry, and strata as young as the Upper Huronian Goodrich quartzite, but does not cut the Cambrian beds of the region. It is regarded as Killarnean.

5. The fifth group of rock types comprises aplites, pegmatites, quartz veins, and basic intrusives, which are not in general germane to the unraveling of the sequence of granitic intrusions in the Southern Complex. These, with the exception of the basic intrusives, are associated as to origin with the divers ages of granites in the area; consequently their grouping here as a unit has no reference to age equivalence, but is merely a convenient method of classification.

The Southern Complex is truly a complex of pre-Cambrian igneous and metamorphic rock types which cover a vast span of time. The term "Republic Granite" coined by Lamey[14] and used by him when referring to the entire area is therefore decidedly a misnomer as so applied, but might be employed if restricted to the post-Huronian, or Killarney, granite in the district.

Heavy accessory mineral studies now in progress at the University of Wisconsin in connection with the igneous rock types of the Southern Complex may lend further corroboration to the intrusive sequence outlined in this paper.

[14] *Ibid.*, pp. 498–99.

GEOLOGY OF EAST BAY, MINNITAKI LAKE, DISTRICT OF KENORA, ONTARIO

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ABSTRACT

The results of a detailed field study of East Bay, Minnitaki Lake, District of Kenora, Ontario, are here given. A sequence of lavas and pyroclastics together with sediments, over 10,000 feet thick, is described. An analysis of the complex of folds and faults in which these beds are involved is presented. As a result of a better understanding of structure the "Keewatin" period was found to consist of two periods of volcanism separated in time by two periods of diastrophism and an intervening period of sedimentation. A similar sequence is known from other areas in the northern sub-province of the Lake Superior pre-Cambrian. The East Bay section is compared with the sections of Vermilion Township, Savant Lake, and Mosher Bay of Manitou Lake.

INTRODUCTION

The northern sub-province of the Lake Superior pre-Cambrian has been studied geologically for many years. As yet, however, owing to its large size, its general lack of commercial mineral deposits, and its structural complexities, no generally acceptable standard geologic section has been established for this region, as has been done in the other portions of the Lake Superior district. Inasmuch as the rocks are largely early pre-Cambrian in age, and since the structures in which they are involved are very complex, it is necessary, in order to work out the geologic history of this region, to study small, well-chosen districts or key areas. When the details of these key areas are well enough known, the relations between them may better be determined. With such an end in view, the writer and his students have been working on a number of such critically located districts in recent years. East Bay of Minnitaki Lake is another such key area.

The geology of this bay has also some added interest by reason of the unusual sedimentary record represented by the interbedded coarse conglomerates and varved slates and by the structures in which both sediments and associated volcanics are involved.

Previous work in this region is recorded in early reconnaissance

surveys by Coleman[1] and Collins[2] and by more recent studies by Hurst[3] and the author.[4]

The writer acknowledges the aid given by Mr. R. M. Grogan and Mr. J. S. Langwill, field assistants, and by the National Research Council, which made a grant to cover field expenses.

STRATIGRAPHY

SUMMARY OF GEOLOGIC HISTORY

Both acid and basic lavas form the oldest series known in this area. They are designated pre-Abram (perhaps Keewatin) since they antedate the main sedimentary series of the district. The Abram series, separated from the earlier volcanics by an important unconformity, is divided into four formations: (1) a thick quartz-porphyry conglomerate with interbedded white arkose and black slate, (2) a varved slate formation with some interbedded arkosite and a little granite-pebble-bearing conglomerate, (3) a graywacke-slate formation, and (4) an iron-bearing formation with associated arkosites, slates, and tuffs. A younger series of basic and intermediate lavas with agglomerates and tuffs, here called the Neepawa volcanics, overlies the Abram series unconformably. Basic intrusive dikes and sills cut the sediments, while a stock of granite and quartz-diorite cuts the younger volcanics. Quartz-porphyry dikes cut the stock.

Sharp folding followed by large-scale faulting has affected the whole sequence.

PRE-ABRAM VOLCANICS ("KEEWATIN")

The oldest rocks of East Bay are volcanics, now largely greenstones and chlorite-schists. These lie in the main along the south side of the lake. Since these lavas, together with another series of

[1] A. P. Coleman, "Second Report on the Gold Fields of Western Ontario," *Ont. Bur. Mines Ann. Rept.*, Vol. V (1895), pp. 55–60.

[2] W. H. Collins, "A Geological Reconnaissance of the Region Traversed by the National Transcontinental Railway between Lake Nipigon and Clay Lake, Ontario," *Can. Geol. Surv. Publ. 1059* (1909).

[3] M. E. Hurst, "Geology of the Sioux Lookout Area," *Ont. Dept. Mines Ann. Rept.*, Vol. XLI, Part VI (1933), pp. 1–33.

[4] F. J. Pettijohn, "Conglomerate of Abram Lake, Ontario, and Its Extensions," *Geol. Soc. Amer., Bull. 45* (1934), pp. 479–506.

TABLE I

FORMATIONS OF EAST BAY, MINNITAKI LAKE, DISTRICT OF KENORA, ONTARIO

Age	Series	Formation	Approximate Thickness in ft.	Remarks
Quaternary	Pleistocene	Late Wisconsin	0–30+	Lacustrine sands and varved clays Glacial drift
		Great Unconformity		
Early Pre-Cambrian	Post-Abram intrusives	3. Quartz-porphyry dikes		Post-granite in age
		2. Granite-diorite stock of Northeast Bay		
		1. Basic dikes and metadiorite		
	Neepawa volcanics	Andesite and dacite porphyries Agglomerates Tuffs Ellipsoidal lavas	3,500+	Post-Abram age not certainly proved
		Unconformity?		
	Abram series	4. Iron-bearing formation	1,000±	Iron formation with arkosites, green schists, and tuffs. Relations to No. 2 and No. 3 not clear
		3. Graywacke-slate	1,000±	Predominantly graywacke, regularly interbedded with slate beds 1–10 or more feet thick
		2. Varved slates	1,300–2,000	Predominantly "ribboned" slates, with some arkosite, graywacke, and *granite*-pebble conglomerates. In part interbedded with No. 1
		1. Quartz-porphyry conglomerate, and arkosite	2,500±	Interbedded with black fissile slates
		Unconformity		
	Pre-Abram volcanics ("Keewatin")	Basic volcanics Acid volcanics	1,000+	Largely "greenstone" and chlorite schists. Often ellipsoidal

volcanics lying along the north of the bay, have been heretofore called Keewatin and have been considered the same age, it seems necessary to present the evidence bearing on their respective ages. On the east side of Twinflower Bay the lavas which occur immediately south of the sediments, here represented by conglomerates and iron formation, have their tops facing north, toward the sediments, indicating, therefore, the older age of these lavas. Also, as may be seen on the geologic map, on the islands in the east part of East Bay the lavas lie north and east of the quartz-porphyry conglomerate member of the Abram series (Fig. 1). The conglomerate is apparently the lowest member of the sedimentary series, since south and west of the latter are found other sedimentary beds with their respective tops all facing south. The lavas, therefore, by reason of their position, northeast of the conglomerate, are the oldest rocks in the sequence.

Lithologically the lavas are not unusual. They are largely composed of light apple-green pillow lavas and their schist equivalents. Some quartz-bearing lavas are associated with them.

ABRAM SERIES

The sediments of this series lie mainly on the islands of East Bay. A careful study of the outcrops on these islands, beginning with those in the middle of the bay near its east end and working southwest to the mainland north of Twinflower Bay and south of Neepawa Island, shows the series to be divisible into three formations.

The lowest is a thick group of interbedded conglomerates and arkosites composed of quartz-porphyry débris and thin beds of laminated, pyritic black slate. The arkose and conglomerates are conspicuous because of their light color—almost white—and the abundance and size, up to 48 inches in diameter, of the quartz-porphyry boulders contained therein. Locally numerous fragments of slate are found in these beds—evidently of intraformational derivation. Under the microscope the arkosic phases clearly show a clastic origin. Because of the abundance of quartz and feldspar, the latter greatly predominating, the angular shape of the grains, and the close association with conglomerates bearing much quartz-porphyry débris, the rock is believed to have been produced by rapid mechanical weathering and redeposition of quartz porphyry detritus.

Above the conglomerate and arkosite is a well-banded or "ribboned" slate, elsewhere described and interpreted as a varved slate.[5] Slate forms the most of this formation; the balance is composed of interbedded graywacke and some coarse sandy and conglomeratic beds. The latter carry granite as well as quartz-porphyry boulders up to 18 inches in diameter. Microscopic examination of a coarse arkosic bed associated with this conglomerate shows that this deposit differs from the white arkoses of the lower conglomerate and arkosite member in that it has fewer and smaller feldspar grains, larger and more quartz grains which dominate over the feldspar in number, and much less undisintegrated felsitic rock débris.

The varved slates grade upward into graywackes with regularly interstratified slates. Graywacke forms 75–95 per cent of this overlying formation. The individual beds, always composed of both graywacke and slate, are usually 1–4 feet thick. They are, in effect, huge varve-like couplets. Graded bedding is abundant and affords much evidence concerning structural position of the beds. A thin section of the graywacke shows this rock to be largely an ill-sorted mixture of quartz and feldspar, the latter subordinate in quantity, together with much fine detritus. The latter is much altered to chlorite and white mica and is, in part, replaced by carbonate. Another section examined was found to be singularly deficient in quartz, and was formed almost wholly of detrital feldspar grains in a chloritized and sericitized matrix. Cataclastic action had rendered the rock schistose.

The three formations described are separated from one another rather arbitrarily, since they grade into one another. The disappearance upward in the section of the white arkosite marks the line between the first two, while the disappearance of the thin ribboned or varved slates marks the division between the second and third.

The conditions of sedimentation have been elsewhere reviewed.[6] It was concluded that the varved slates were seasonally deposited clays and silts. They were apparently laid down in quiet fresh-water

[5] F. J. Pettijohn, "An Early Pre-Cambrian Varved Slate in Northwestern Ontario," manuscript submitted to Publications Committee, Geol. Soc. Amer. (1935).

[6] F. J. Pettijohn, "An Early Pre-Cambrian Varved Slate in Northwestern Ontario." Manuscript submitted to Publications Committee, Geol. Soc. Amer. (1935).

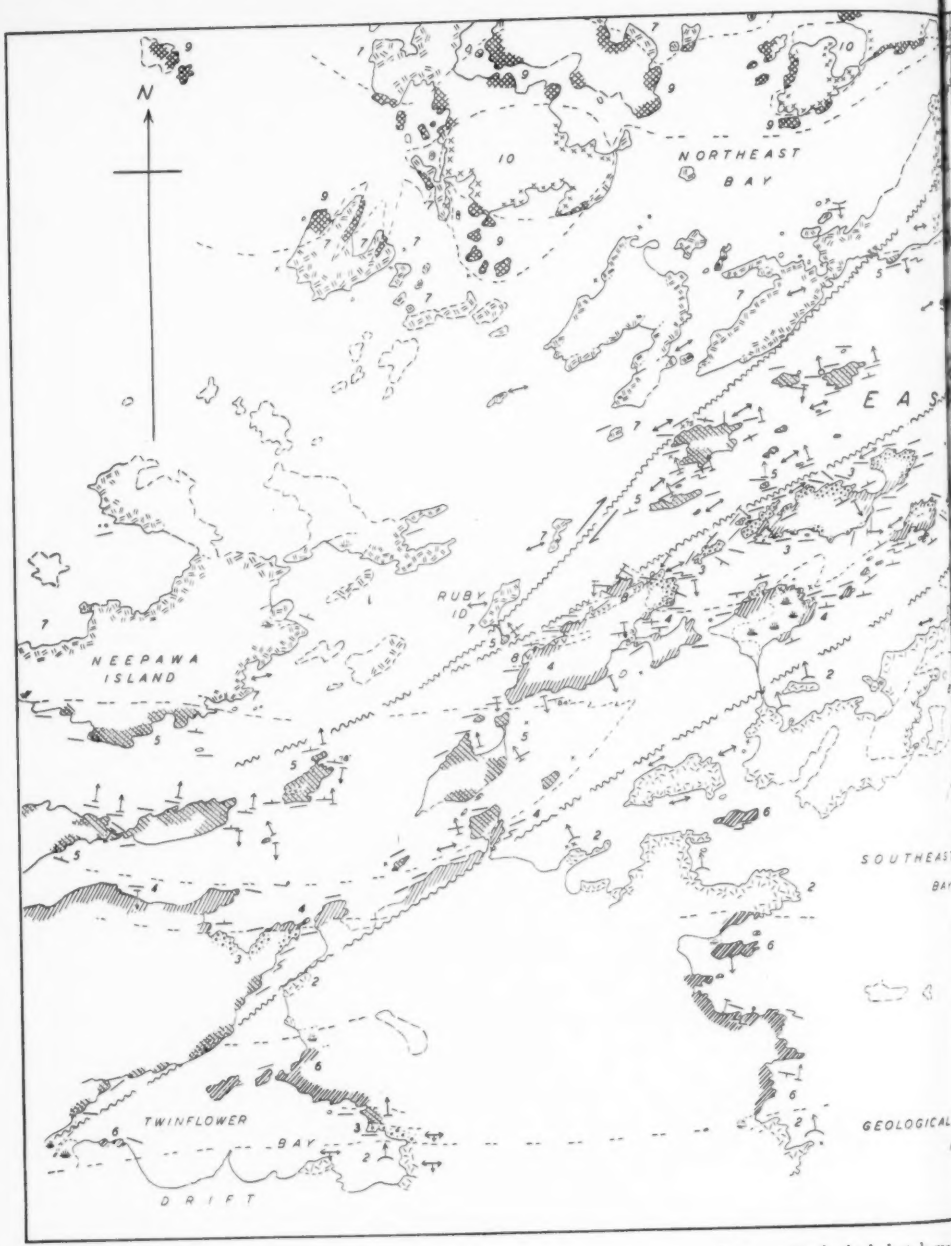
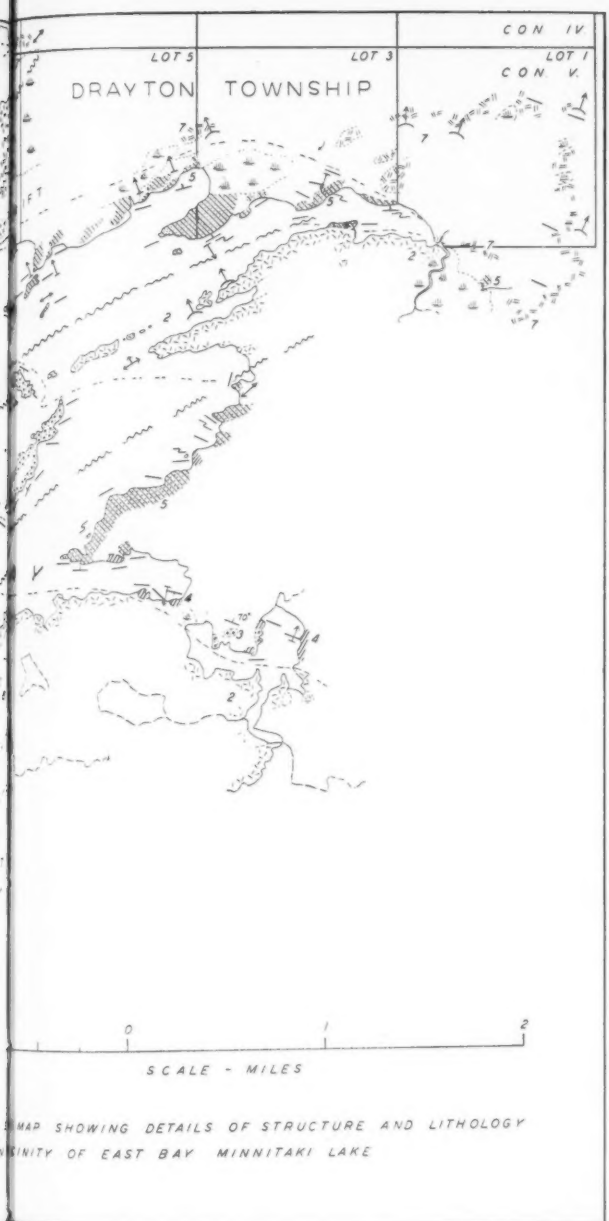


FIG. 1.—Geological sketch map



MAP SHOWING DETAILS OF STRUCTURE AND LITHOLOGY
INITY OF EAST BAY MINNITAKI LAKE

LEGEND

EARLY PRE-CAMBRIAN

INTRUSIVES

10 GRANITE

9 QUARTZ DIORITE

8 BASIC INTRUSIVES

NEEPAWA VOLCANICS

7 ANDESITE PORPHYRIES AND AGGLOMERATES

ABRAM SERIES

6 IRON FORMATION

5 GRAYWACKE-SLATE

4 VARVED SLATE

3 CONGLOMERATE AND WHITE ARKOSITE

OLDER KEEWATIN LAVAS

2 BASIC VOLCANICS

1 ACID VOLCANICS

SYMBOLS

SWAMP

STRIKE AND DIP OF BEDDING

STRIKE OF BEDDING

STRIKE AND DIP OF SCHISTOSITY

TOP OF BEDS AS INDICATED BY CROSS-BEDDING

TOP OF BEDS AS INDICATED BY GRADATION OF GRAIN

TOP OF FLOWS AS SHOWN BY SHAPE OF PILLOWS

PLAN OF DRAG FOLDING

GEOLOGICAL BOUNDARY DEFINED

GEOLOGICAL BOUNDARY ASSUMED

FAULT

y of East Bay, Minnitaki Lake

lakes, whereas the coarse arkosites and conglomerates represent periodic invasions of this environment, presumably by torrential fluvial wash from adjacent highlands. The lacustrine environment into which the gravels periodically encroached was gradually replaced by an environment in which the sandy silts and clays—ultimately forming the graywacke-slate formation—were laid down.

The iron-bearing strata stand apart from the other formations of the Abram series since they are found only on Twinflower Bay and on Southeast Bay. The relation of the iron-bearing formation to the other formations is not clear, and it may possibly be their time equivalent, since they are apparently replaced in the sequence by the iron formation. The latter is diverse in character and in a single outcrop may be found thin magnetic bands interstratified with ordinary slates, cherty slates, graywacke, green schists, and tuffs. The manner of origin of this type of iron-bearing formation is not known. It is apparently similar in character and origin to that found on Abram Lake,[7] Savant Lake,[8] and Knife Lake.[9]

POST-ABRAM (NEEPAWA) VOLCANICS

On the north side of Neepawa Island and on the north end of Ruby Island, as well as on the mainland north and northeast of East Bay, is a thick series of andesite porphyries and related agglomerates and tuffs. These occupy the whole area of Northeast Bay of Minnitaki Lake, and are known to extend west into Troutfish Bay and Lyons Bay and to appear in some places on the south shores of Abram Lake. Pillow structures are not common. The porphyritic character of the lavas is striking, as are the thicker, lighter-colored, and abundant tuffs and agglomerates. Microscopic study shows the porphyries to be characterized by phenocrysts of plagioclase (acid oligoclase) and green hornblende set in a pilotaxitic groundmass. Since the feldspars now contain much epidote, it seems likely that they were once

[7] F. J. Pettijohn, "Conglomerate of Abram Lake, Ontario, and Its Extensions," *loc. cit.*, pp. 495, 498.

[8] Gordon Rittenhouse, *Geology of a Portion of the Savant Lake Area, Ontario.* A dissertation submitted to the Faculty of the Division of the Physical Sciences in candidacy for the degree of Doctor of Philosophy, University of Chicago (1935), pp. 20–33.

[9] J. T. Stark, "Agawa Iron Formation of Northeastern Minnesota," *Econ. Geol.*, Vol. XXIV (1929), pp. 528–41.

more calcic and metamorphism has caused the separation of epidote. Very probably the rock was an andesite.

The relations of these volcanics (lithologically quite unlike the pre-Abram volcanics south of East Bay) to the Abram series are not clear. They are apparently in contact with the graywacke-slate formation on Neepawa Island and on the mainland in Drayton Township. No conglomerate was found at the contact. In lot 5, Con. I, both sediments and volcanics have their tops facing north so that the lavas are younger, unless there is a fault contact between them. In lot 3, however, the sediments have tops facing south, though the nearest lava outcrops, a quarter of a mile to the northeast, have north-facing tops. If these observations are correct, either a fault or a marked unconformity lies along the boundary between lavas and sediments. The writer favors the latter interpretation, though final proof of the correctness of this view has not been obtained.

From their occurrence on Neepawa Island these lavas and associated volcanics may be called the Neepawa volcanics.

POST-ABRAM INTRUSIVES

Numerous sills and dikes of basic character and a few larger bodies of metadiabase or metadiorite cut the sediments of East Bay. In Northeast Bay is a stock, with diorite border phase and granite center, which cuts the andesite porphyries and agglomerates. The diorite border phase is cut by the granite, which is cut in turn by quartz-porphyry dikes. If the volcanic country rock is post-Abram, as seems probable, then the stock and associated dikes are also post-Abram. Definite age relations between the acid porphyry dikes of Northeast Bay and the basic dikes of East Bay were not obtained. Very possibly the basic sills and dikes were contemporaneous with the Neepawa volcanics, and represent feeders for these flows.

STRUCTURE

STRUCTURAL CRITERIA

Unraveling the structural features of the early pre-Cambrian involves giving particular attention to the respective position of top and bottom in the vertical or near-vertical beds, measuring and plotting observed strikes, and accurately mapping formation boundaries. Neither the amount nor the direction of dip is significant, ow-

ing to the abundance of overturned strata and to the uniformly high or near-vertical attitude of most beds. The pitch and plan of drag folds are, however, useful in structural analysis.

The orientation of top and bottom in the sediments was determined largely by a study of graded bedding in the finer sediments. Though this criterion has been questioned,[10] it was found to be reliable in this and other similar areas. The orientation of the lavas[11] was determined by study of the shape of the pillows in the ellipsoidal zones. This has likewise proved to be a very reliable criterion of top orientation.

FAULTING

The strata of East Bay have been both sharply folded and much faulted. The criteria for determination of the position and character of the faults of the type found here have been given elsewhere.[12] The transgressive contacts between formations, i.e., the contacts which are themselves oblique to the measured strike of the beds within the formation and the anomalous relations between clearly determined tops and bottoms of beds, such as two adjacent, vertical, and unlike beds with their respective tops facing each other, are the most important criteria for these faults. Confirmatory evidence consists largely of extremely schistose zones along the implied faults, pyritization and carbonatization along the same lines, and, in one instance, slickensided and polished shear surfaces and gouge.

Ruby Island fault.—This fault, trending N. 45° E., separates the Abram sediments from the younger or Neepawa volcanics throughout most of its course. It passes through Ruby Island, hence its name. It is lost northeastward in the greenstones of Drayton Township, and its extension southwestward is not known owing to lake cover. It is markedly transgressive to the strike of both lavas and sediments, and apparently cuts across several formations. On Ruby

[10] H. C. Cooke, "Anomalous Grain Relationship in the Caldwell Quartzites of Thedford District, Quebec," *Proc. and Trans. Roy. Soc. Can.*, 3d ser., Vol. XXVII, Sec. 4 (1931), pp. 71–74.

[11] F. J. Alcock, "Flinflon Map Area, Manitoba and Saskatchewan," *Can. Geol. Surv. Summary Rept. 1922*, Part C (1923), p. 11.

[12] F. J. Pettijohn, "Conglomerate of Abram Lake, Ontario, and Its Extensions," *loc. cit.*, pp. 504–5; J. E. Hawley, "Seine or Coutchiching?" *Jour. Geol.*, Vol. XXXVIII (1930), pp. 521–47.

Island the zone of shear is indicated by striae and slickensided schists. These indicate the last movement to have been upward and northeastward on the northwest side of the fault. The striae pitch about 25° southwest in the plane of the fault.

East Bay fault.—This structure strikes about N. 65° E., parallel to the prevailing schistosity of the region. It is determined largely on the basis of the anomalous relations between the sediments which lie both north and south of it. The beds on the north—the graywacke-slate formation—are in the main north-facing, whereas those on the south—the conglomerate-arkosite and varved slate formations—are south-facing. Moreover, the fault truncates, at a low angle, the strike of the beds which lie to the south. The graywacke-slate formation is thus brought progressively in contact with, beginning in the northeast and going southwest, (1) the older greenstones, (2) the conglomerate and arkose, and (3) the varved slates.

Twinflower fault.—This fault, following along the northwest coast of Twinflower Bay, is about parallel to the East Bay fault. It truncates the syncline of Twinflower Bay involving the iron formation, and extends northeast roughly parallel to the south shore of East Bay. It separates the sediments of East Bay, the tops of which face south, from the southern or older lavas with their north-facing tops. Its northeastern limit, like that of the East Bay fault, is unknown.

FOLDING

As noted above, the strata of East Bay are largely vertical. The folds in which they are involved are thus nearly isoclinal. Owing to faulting subsequent to folding, the original anticlines and synclines are incomplete both in symmetry and along the strike. The graywacke-slate formation of the Abram series and the Neepawa volcanics north of the East Bay fault and south of the Ruby Island fault form the south limb of a syncline, the axis of which lies somewhere in the Neepawa greenstones themselves. Since the Ruby Island and the East Bay faults join southwest of Ruby Island, the structure described lies within a fault block, wedge-shaped in plan, with nearly vertical sides.

The strata south of the East Bay fault form the north limb of a syncline, the southern limb of which is largely cut out by the Twinflower fault, except in the territory just west of the entrance to

FIG. 2.—Pre-Cambrian sedimentary rocks of northwestern Ontario

Twinflower Bay, where it is present in normal manner. On Twinflower Bay proper, and between this bay and Southeast Bay, is a synclinal structure involving the iron formation. The structure of the sediments south of the east end of East Bay and north of Southeast Bay is not known, but it is apparently also synclinal.

The drag folds in the sediments all show the regional pitch to the southwest at high angles, 30°–85°. In the main, the plan of the minor drag folding seems to be consistent with such direction of pitch and with the known top-bottom orientation of the beds. Large-scale drag folding in the varved slate and quartz-porphyry conglomerate, however, may be related to the movement on adjacent faults. The only direct evidence regarding movement on the faults are the striae on Ruby Island. The movement evidently had a large horizontal component in the plane of the fault, and the north side seems to have moved northeast. This is consistent with the larger drag folding referred to, and may explain the steep pitch observed on these folds.

CONCLUSIONS

The faults truncate the folds. It is concluded, therefore, that these two types of structure are of different ages, the faulting being the younger. The steep pitch of the drag folding is best explained if these minor folds are regarded as late developments produced by drag along the faults themselves. Hawley[13] and Thomson,[14] however, postulate a simultaneous origin for all structures in their respective fields of study.

If any faulting took place in conjunction with the folding of the sediments, the writer is not aware of it. The contact, mentioned elsewhere, between the graywacke-slate member and the Neepawa volcanics, excluding the Ruby Island fault, may itself be a fault contact. If so, it is an early fault, possibly of the thrust type, subsequently folded to its present vertical position and offset by the Ruby Island fault. The alternate explanation is that it is an unconformity, in which case a period of diastrophism post-Abram and pre-Neepawa is implied.

[13] J. E. Hawley, *op. cit.*, pp. 521–47.

[14] James E. Thomson, "Geology of the Manitou-Stormy Lakes Area," *Ont. Dept. Mines Ann. Rept.*, Vol. XLII, Part IV (1933), pp. 1–40.

CORRELATION

East Bay is a key area—i.e., an area subjected to detailed structural and stratigraphic analysis. Other districts so studied include Vermilion Township,[15] Savant Lake,[16] Manitou Lake (Mosher Bay),[17] Beresford Lake,[18] Rainy Lake,[19] and Knife Lake.[20] The relations between the first three areas named and East Bay are discussed here, and the general correlations indicated in Table II (see Fig. 2). Inspection of the latter will show a general similarity in sequence in all districts. An older series of lavas, a principal sedimentary series, and a younger series of volcanics characterized by their more acid character and great abundance of pyroclastic materials, are present in each district.[21] That the sediments rest unconformably on the older volcanics is well shown in the Savant area, where Rittenhouse[22] found the basal conglomerate truncating the strike of the older lavas. This relation is further substantiated in Vermilion Township, where the basal beds of the Ament Bay formation, in contact with a quartz-porphyry body which intrudes the older volcanics, contain débris from the porphyry itself.

[15] F. J. Pettijohn, "Stratigraphy and Structure of Vermilion Township, District of Kenora, Ontario," *Geol. Soc. Amer. Bull. 46* (1935), pp. 1891–1908.

[16] Gordon Rittenhouse, *op. cit.*

[17] James E. Thomson, *op. cit.*

[18] J. F. Wright, "Geology and Mineral Deposits of the Northern Part of Beresford Lake Map Area, Southeastern Manitoba," *Can. Geol. Surv. Summary Rept.* (1923), Part B, pp. 86–104.

[19] F. F. Grout, "Coutchiching Problem," *Geol. Soc. Amer. Bull. 36* (1925), pp. 351–64.

[20] J. W. Gruner, "A Newly Discovered Major Unconformity in the Huronian Rocks of Northern Minnesota," *Proc. Lake Superior Mining Inst., 27th Ann. Meeting* (1929), pp. 180–87.

[21] The younger series of volcanics was not recognized by James E. Thomson in his survey of the Manitou area. See "Geology of the Manitou-Stormy Lakes Area," *loc. cit.* Studies by the writer in the summer of 1935 show that the lavas called Keewatin by Thomson, which lie north of the sediments of Mosher Bay, rest on the slate member of that series and have their tops, as shown by pillow structures, directed away, or northward from the near-vertical plane of contact. Such relations prove a younger age for these volcanics. This difference in interpretation of sequence does not detract, however, from the excellent analysis of stratigraphy and structure given by Thomson in his report on this area.

[22] *Op. cit.*, p. 16.

FIG. 2.—Pre-Cambrian sedimentary rocks of northwestern Ontario

TABLE II

CORRELATION CHART OF EARLY PRE-CAMBRIAN

East Bay	Vermilion Township	Savant Lake (After G. Rittenhouse)	Manitou Lake (After James E. Thomson)
Quartz-porphyry dikes Granite, quartz-diorite	Granite-porphyry	Granite Granite-gneiss	Granite Quartz-porphyry
Metadiorite Basic dikes	Metadiorite† Basic dikes	Metadiorite	Basic intrusives
Neepawa volcanics† (andesite porphyries and agglomerates)	Tuff and agglomerate‡	Handy Lake volcanics (acid lavas and agglomerates)	Volcanics§ (lavas and agglomerates)
Unconformity	Unconformity	Unconformity ?	Unconformity
Abram Series: Graywacke-slate (Iron formation of Twinflower Bay)	Abram Series: Daredevil formation: Graywacke-slate	Savant Series: Upper: Upper graywacke member	Manitou Series: Graywacke-slate with quartzite and arkosite
Abram Series: Varved slates with some granite-pebble bearing conglomerate and arkosite (Iron formation of Twinflower Bay)	Abram Series: Daredevil formation: Andesite-tuff	Savant Series: Upper: Upper iron-bearing member	
	Abram Series: Daredevil formation: Graywacke	Savant Series: Upper: Lower graywacke member	
	Abram Series: Daredevil formation: Rhyolite and tuff	Savant Series: Upper: Lower iron-bearing member	
Abram Series: Quartz-porphyry conglomerate and white arkosite	Abram Series: Ament Bay formation: Massive arkosite and granite-pebble conglomerates	Savant Series: Lower: Upper conglomerate member	Manitou Series: Granite-pebble conglomerates and arkosite / Tuff and agglomerate
	Abram Series: Ament Bay formation: Laminated arkosite		
	Abram Series: Ament Bay formation: Basal breccia	Savant Series: Lower: Lower conglomerate member	
Unconformity	Unconformity	Unconformity	Unconformity
(Quartz-porphyry and granite)*	Quartz-porphyry (granite)*	(granite)*	(granite)*
Older volcanics (greenstones, chlorite schists, and iron formation)	Keewatin: Younger gray lavas and agglomerate Keewatin: Patara sediments Keewatin: Older greenstones	Jutten volcanics (basic lavas and iron formation)	"Keewatin" lavas (acid, basic, with tuff and agglomerate) (iron formation)*

* Known only from pebbles in overlying conglomerates.

† May be pre-Abram.

‡ "Slate-pebble conglomerate" of early reports.

§ Not differentiated by Thomson from "Keewatin."

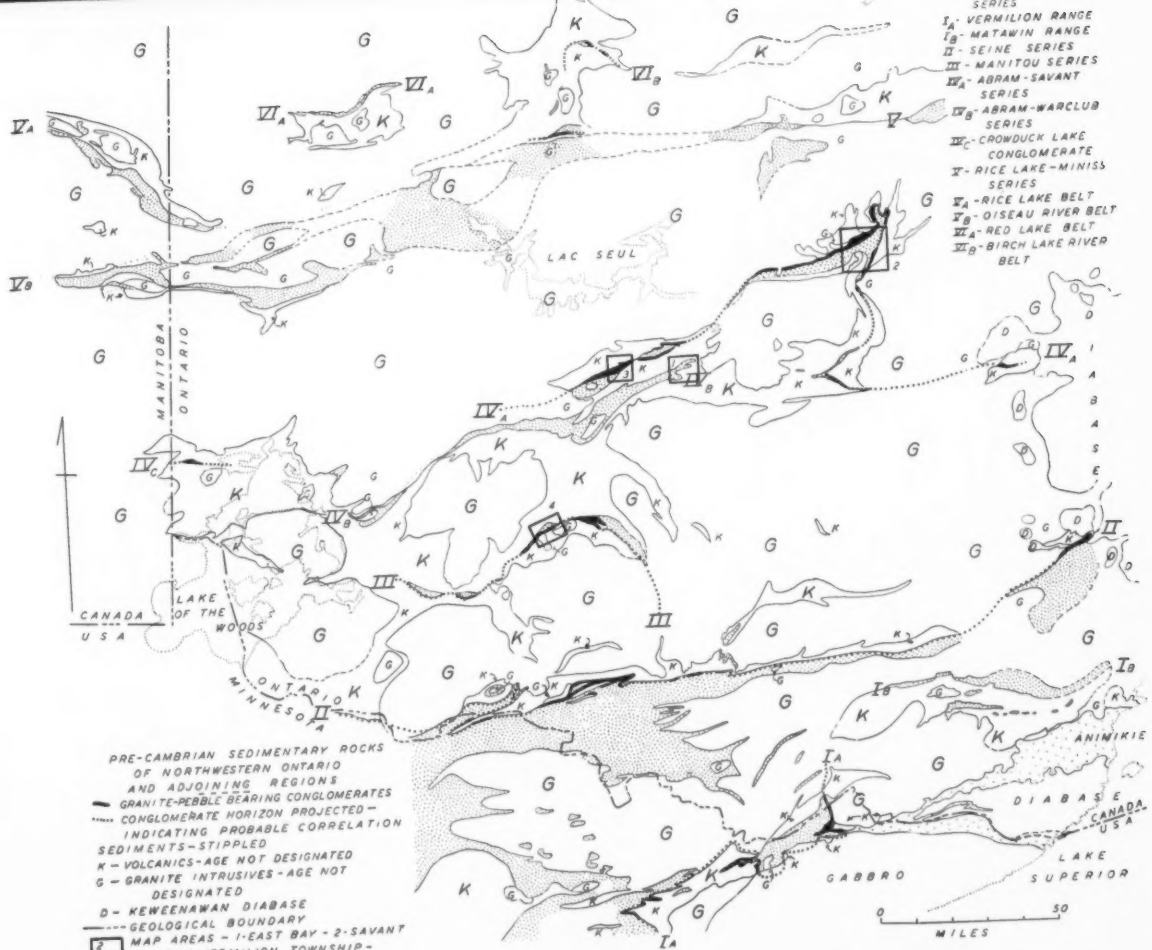


FIG. 2.—Pre-Cambrian sedimentary rocks of northwestern Ontario

The sediments are everywhere roughly divisible into two formations, the lowest one of which is largely a torrential, continentally deposited conglomerate and associated arkosite, while the upper formation consists of finer clastics, mainly graywackes and slates. Some contemporaneous volcanism is known in all four regions, especially in the Manitou district, where conglomerate is replaced along the strike by agglomerate,[23] and in the Savant area, where tuffs and agglomerates are interbedded with normal sediments throughout the whole section. The sediments of East Bay are freest from volcanic admixtures. The iron formation is present in two of the four areas, and is associated with the finer sediments and tuffs.

The relation of the sediments to the younger volcanics is not everywhere equally clear. An unconformity apparently separates these effusives from the sediments in both the Savant and Manitou districts, as suggested by the transgressive nature of the contact between the sediments and the lavas. On Savant Lake and on Mosher Bay on Manitou Lake the younger volcanics rest on several different formations in different places.[24] A similar relationship may also prevail on Abram and Pelican lakes near Sioux Lookout.

The entire sequence in all districts is cut and invaded by both basic and acid intrusives. The former appeared first, and are cut by the latter. Quartz-porphyry is younger than the granite on Minnitaki Lake. Except in Vermilion Township, earlier or pre-sedimentary intrusives are unknown except as pebbles in the conglomerates. Granite is everywhere an important constituent of the coarse conglomerates, and is only locally supplanted by other materials.

CORRELATION WITH MORE REMOTE AREAS

The writer is of the opinion that it is yet too early to carry correlations into more distant areas in this sub-province, and much too early to make correlations of any value at all between this sub-province and other parts of the Lake Superior region. The recognition of two distinct periods of effusive volcanism renders the term "Keewatin" obsolete or inadequate, and greatly complicates the problem of correlation with distant areas.

[23] Thomson, *op. cit.*, p. 14. [24] *Ibid.*, Fig. 2; Rittenhouse, *op. cit.*, p. 36.

As stated by the writer elsewhere, there are in the northern subprovince some five major belts of sedimentary rocks which lie approximately parallel to one another and extend for varying distances from west to east across the region (Fig. 2). These are, from south to north, (I) the Knife Lake-Ogishke series, (II) the Seine (and Steeprock) series, (III) the Manitou series, (IV) the Abram and Savant series, and (V) the Manigotagan-Miniss series (extending from southeastern Manitoba northeastward to Lake St. Joseph and Miniss lakes). The sediments of East Bay belong to the fourth major belt. It seems probable to the author, on evidence to be presented in a forthcoming paper, that the sediments of these several belts are not all of the same age. Some are probably older than the sediments of East Bay, and some are probably younger.

PHYSIOGRAPHIC HISTORY OF A PORTION OF THE PERRIS BLOCK, SOUTHERN CALIFORNIA

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ABSTRACT

Adjacent discordant surfaces of peneplanation in the crystalline rocks of southern California usually have been ascribed to the faulting of one surface. The Perris block is a structural unit on which there are old erosional surfaces at two levels. Field mapping has proved that this discordance is not due to faulting but represents the truncation of the block at two different levels by erosion. This was possible only through two separate periods of partial burial of the block. Now that the block has been exhumed, the high- and low-level erosional surfaces and various instances of superposed drainage remain as evidence of its former burial.

INTRODUCTION

The portion of the Perris block which is herein discussed lies mainly in the Elsinore Quadrangle, southern California. It is some 50–75 miles southeast of Los Angeles and comprises the area (Fig. 1) of approximately 500 square miles which lies between the towns of Corona, Riverside, San Jacinto, and Elsinore. The block was first named by English.[1] It is the structural unit bounded by the San Jacinto rift on the northeast and the Elsinore graben on the southwest. In its entirety, this unit extends beyond the area under discussion for an unknown distance to the southeast, and northwest to the base of the San Gabriel Mountains. In this paper, however, only a portion of it is considered when the term "Perris block" is mentioned. This is the 25-mile segment between Domenigoni Valley in the southeast and Arlington Valley on the northwest which exhibits what has been known generally as the Perris "peneplain."

The distribution and structure of the rocks which were revealed by field mapping of this portion of the Perris block[2] lead to the conclusion that the physiographic history of the block was fairly com-

[1] W. A. English, "Geology and Oil Resources of the Puente Hills Region, California," *U.S. Geol. Surv. Bull. 768* (1925), p. 54.

[2] P. H. Dudley, "Geology of a Portion of the Perris Block, Southern California," *Calif. Jour. Mines and Geol., Calif., Div. Mines, State Mineralogist's Rept.*, Vol. XXXI (1935).

plex and different from what a casual inspection would lead one to believe. It was found that the region exhibits two distinct old-age surfaces (Fig. 2). One of these, having an average elevation of 1,700 feet, is here designated the "Perris surface"; and the other, at approximately 2,100 feet elevation, is called the "Gavilan-Lakeview peneplain." Each of these features is a surface of truncation which

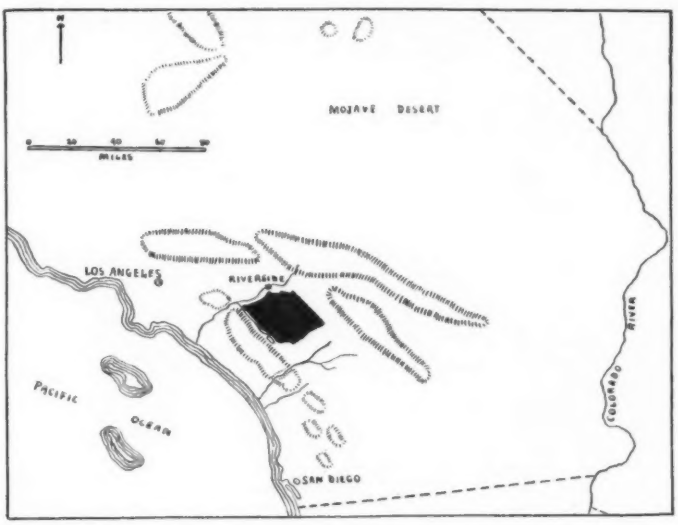

FIG. 1.—Key map showing location of the Perris block (solid black), Southern California.

has been made possible only by the burial of surrounding territory. The exhumation of the buried topography has been sufficient to expose these high- and low-level old erosion surfaces as well as several instances of superposed drainage on the block. Faulting to the southwest of the block has complicated this superposed drainage pattern.

AREAL GEOLOGY AND STRUCTURE

The determination of the areal geology and structure of the Perris block was accomplished as a prelude to the study of its physiographic features. While the rocks are dominantly crystalline, important

amounts of sediments occur in certain parts of the area. The rock types are given in Table I.

The Elsinore metamorphics consist of a variety of meta-sediments and meta-volcanics which have been assigned, on fairly conclusive

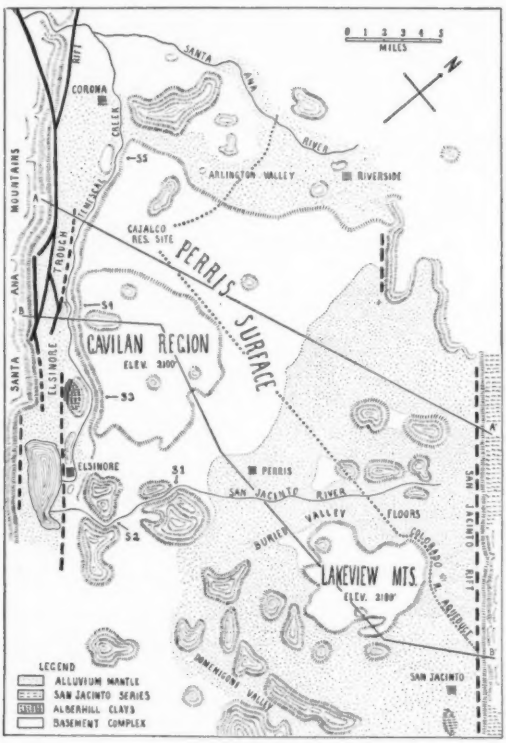

FIG. 2.—Map of the Perris block with diagrammatic hachuring to emphasize the main features of relief.

evidence, to the Triassic. There is a distinct time interval between the formation of these rocks and the unaltered intrusives of the region which have been assigned to a late Jurassic age. Apparently the earliest of the intrusives is the Temescal dacite-porphyry which appears to be a hypabyssal member. The plutonic members range

from various gabbros into norite and finally into diorites and monzonite. While there is an established sequence among most of these intrusives, from the Temescal dacite-porphyry to the Cajalco quartz-monzonite, their age difference probably is not great. It is likely that they all were intruded at the same time as the Sierra Nevadan batholith which, latest evidence shows, was intruded between the Mariposa (upper but not latest Jurassic) and the opening of the Cretaceous.[3] The Alberhill clays, which include marine, lacustrine, and residual facies are of Eocene (Martinez) age[4] and

TABLE I

Age	Formation
Quaternary	Alluvium
Pleistocene to Pliocene	San Jacinto sediments
Eocene	Alberhill clays
Late Jurassic (?)	Cajalco quartz-monzonite
	Steele Valley granodiorite
	Lakeview quartz-hornblende-diorite
	Estelle quartz-diorite
	Perris quartz-diorite
	Gabbro
	Virginia quartz-hypersthene norite
	Temescal dacite-porphyry
Triassic	Elsinore metamorphics

overlie the crystalline basement of the Perris block at certain locations along its southwest margin. The San Jacinto sediments are a series of continental sandstones, shales, and conglomerates of Lower Pliocene to mid-Pleistocene age[5] which can be seen to overlie the

[3] N. E. A. Hinds, "Jurassic Age of the Last Granitoid Intrusives in the Klamath Mountains and the Sierra Nevada, California," *Amer. Jour. Sci.*, Vol. XXVII (1934), pp. 182–92.

[4] G. A. Waring, "Groundwaters in the San Jacinto and Temecula Basins, California," *U.S. Geol. Surv. Water Supply Paper 429* (1919), p. 70; B. E. Moore, *Stratigraphy of the Santa Ana Mountains, California*, unpublished Doctor's thesis, Calif. Inst. Technology (1930), p. 73; J. C. Sutherland, "Geological Investigation of the Clays of Riverside and Orange Counties, Southern California," *Calif. Jour. Mines and Geol., Calif. Div. Mines, State Mineralogist's Rept.*, Vol. XXXI (1935), pp. 58–63.

[5] C. Frick, "Extinct Vertebrate Faunas of the Badlands of Bautista Creek and San Timoteo Canyon, Southern California," *Univ. Calif. Dept. Geol. Bull. 12* (1921), p. 190. While Frick divides these sediments into three facies which he gives local names, he does not name the series as a whole. Since the age of the various members is not

bedrock in and around the southeastern portion of the block. It is probable that they also underlie the alluvium which covers much of the eastern half of the block. Well logs show that this combined blanket of sediments through which only the peaks and ridges of the underlying basement project is commonly 200–600 feet thick and in one locality is over 1,500 feet thick.[6] This sedimentary cover is absent in the western half of the block.

Important faults bound the Perris block on the northeast and southwest. Field mapping within the block, however, has proved that the exposed crystalline rocks show no important dislocation. This lack of faulting within a block adjacent to regional faults was also witnessed by Hudson,[7] in the Cuyamaca region of San Diego County, southeast of the present area, where he accomplished detailed areal mapping of the crystalline rocks. It seems probable that the eastern half of the Perris block, which is partially buried, is undisturbed by important faults, in spite of the fact that Frick mentions considerable dislocation around its eastern corner[8] and that local faulting may be necessary to explain the fact that the sedimentary cover on the block north of the Lakeview Mountains and near the San Jacinto rift is over 1,500 feet deep.[9] The most important question bearing on dislocation in the eastern half of the block is the origin of the monadnock-like masses which Hill[10] believes are due to faulting. It would seem, however, that the stresses causing such necessarily complex dislocation should be reflected in the western half of the block, where disturbance is notably absent. Furthermore, there is no direct field evidence of dislocation around these monadnock-like masses. If buried faults exist, there should be

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greatly different and they are all continental deposits, it is believed that confusion can be avoided by referring hereafter to the collective series simply as the "San Jacinto sediments."

[6] Waring, *op. cit.*

[7] F. S. Hudson, "Geology of the Cuyamaca Region of California," *Univ. Calif. Dept. Geol. Bull. 13* (1922), p. 182.

[8] Frick, *op. cit.*, pp. 290–91.

[9] This depth is located some 3 miles north of the northern tip of the Lakeview Mountains. See Waring, *op. cit.*, p. 43.

[10] R. T. Hill, *Southern California Geology and Los Angeles Earthquakes* (Los Angeles: Southern Calif. Acad. Sci., 1928), p. 168.

at least scattered instances of recurrent movement which would be reflected in the alluvial cover, since the region surrounding the Perris block is one of fault activity. Finally, the geographic arrangement of the monadnock-like masses is irregular; and in certain sections, as north of Domenigoni Valley, their crescentic spacing strongly suggests that they are the projecting divides between buried stream valleys. These various lines of reasoning indicate that the crystalline bosses projecting through the sedimentary cover over most of the eastern half of the block are simply erosional protuberances from the underlying bedrock rather than small fault blocks raised along buried lines of dislocation.

EARLY LAND FORM OF THE PERRIS BLOCK

There are three erosional surfaces of distinctly different age which have been recorded on the Perris block. The earliest of these is designated the "early land form"; the second is called the "Perris surface"; and the latest is designated the "Gavilan-Lakeview peneplain."

Present remnants of the early land form which formerly constituted the entire cut surface of the Perris block still exist at various places on the block. These remnants are, first, the partially buried floor of Arlington Valley on the northwest margin of the block and the valley wall which ascends from it to the Perris surface; second, the partially buried floor of Elsinore trough on the southwest margin of the block and the valley wall which ascends from it to the Perris surface; third, the buried valleys lying between the monadnock-like peaks of the eastern half of the block (Fig. 3). The evidence of well logs shows that the buried valley floors in the eastern half of the block lie considerably below the level of the neighboring Perris surface. Along the boundary of the block, these valleys have been incised to a bedrock elevation approximately equivalent to that of the floor in Arlington Valley and the unfaulted portion of the floor of Elsinore trough.

Most of the early land form has been destroyed by the development of the Perris surface, which partially truncated it at lower levels, and the Gavilan-Lakeview peneplain, which at higher levels truncated what had not been removed in the development of the

Perris surface. It is impossible, of course, to hazard more than a rough estimate of the total early land form, but the most logical cross sections (Fig. 4) which can be reconstructed from the present topography lead one to believe that it was a surface of early maturity. While it is difficult to tell much about the drainage of the early land form, there are certain suggestions that it had little relation to the course of present streams traversing this region. For instance,

FIG. 3.—View 3 miles northwest of Perris, northeast toward the buried valleys and the monadnock-like bosses in the eastern half of the block. The early land form emerges in the foreground to join the Perris surface.

well-log evidence shows that the buried valley floors of the eastern portion of the Perris block deepen toward the northeast in a direction which is reverse to the course of San Jacinto River, now traversing the overlying sediments. Similarly, well-log evidence in Arlington Valley[11] indicates a pronounced buried canyon which deepens to the northeast in a direction opposite to the course of the present Santa Ana River.

PERRIS SURFACE

The Perris surface will henceforth be considered as the essentially horizontal surface which has been cut across the basement complex of the Perris block at an average elevation of 1,700 feet (Fig. 5). The highest elevation of this old erosional surface lies 3 miles north-

[11] R. Eckis, "Geology and Ground Water Storage Capacity of Valley Fill," *Calif. Div. Water Resources Bull. 45* (1935), p. 171.

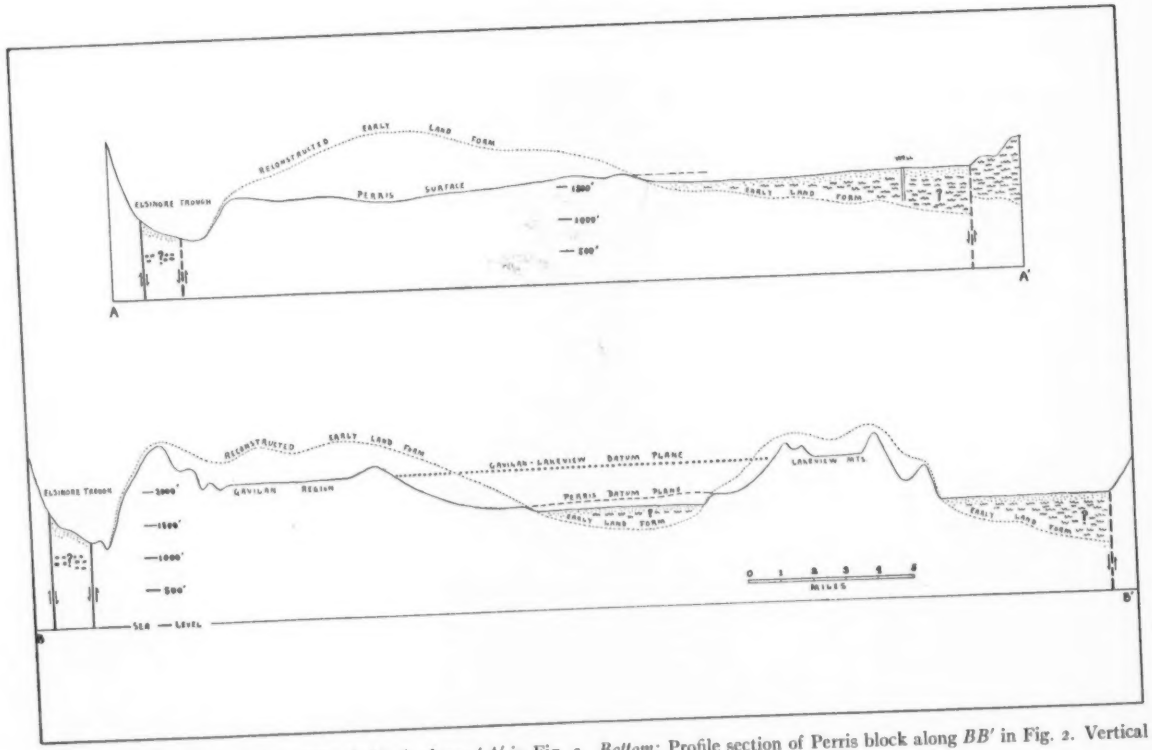

FIG. 4.—*Top:* Profile section of Perris block along *AA'* in Fig. 2. *Bottom:* Profile section of Perris block along *BB'* in Fig. 2. Vertical scale of both profile sections exaggerated to ten times the horizontal scale. Legend same as Fig. 2.

west of Perris, and it slopes gently north and south from this point. While the Perris surface is confined mainly to the northwestern portion of the block, some of the monadnock-like peaks which protrude through the sedimentary cover of the eastern half of the block possess rock-cut benches which occur above the alluvium burying the old valleys and which correspond in elevation with the Perris surface.

Certain authors, including Dickerson,[12] English,[13] and Hill,[14] have used the term "peneplain" to describe the visible surface of low

FIG. 5.—View north showing the intersection between the Perris surface and the early land form which emerges from the sedimentary cover of the block on the right. Picture taken at same point as Figure 3.

relief, extending over most of the Perris block at the elevation of 1,500–1,900 feet. This surface unfortunately includes the Perris surface, as here defined, as well as the surface of the sedimentary fill which covers the block over most of its eastern portion (Figs. 2 and 4). Such a designation has arisen through underestimation of the depth and importance of the sedimentary cover.

[12] R. E. Dickerson, "The Martinez and Tejon Eocene and Associated Formations of the Santa Ana Mountains, California," *Univ. Calif. Dept. Geol. Bull. 8* (1914), pp. 259–60.

[13] English, *op. cit.*, p. 54. [14] Hill, *op. cit.*, p. 168.

It is obvious that the term "peneplain" applied in such fashion to a composite cut and deeply filled surface is inaccurate. Davis' definition of this term, which he originated and which he believed was particularly well exemplified by the Great Plains region of Eastern Montana, involves a gently undulating cut surface, namely, the penultimate surface developed in the humid erosion cycle.[15] Thus, the term "peneplain" is incorrectly used to describe the cut and filled surface of the Perris block. Furthermore, it is doubtful whether the term can be used to describe even the Perris surface because of the existence of the Gavilan region and the Lakeview Mountains overlooking it. While much of the Perris surface possesses low relief, the Gavilan region, which is essentially a truncated monadnock thereon, must have had an original relief considerably in excess of its present 400-foot elevation above the Perris surface. Similarly, the Lakeview Mountains are the truncated remnant of a large monadnock-like mass rising today some 400 feet above the bench cut at their base by erosion producing the Perris surface. These mountain masses are 5–8 miles in diameter and would have a really consequential height if their truncated tops were restored. In view of these facts, it is probably best to designate the Perris surface an "oldland," in the sense as suggested by a recent paper on the terminology of erosional surfaces,[16] rather than a peneplain.

RELATION OF THE EARLY LAND FORM TO THE PERRIS SURFACE

After defining the early land form and the Perris surface, as has been done, it is best to prove that the former is truncated by the Perris surface, and therefore is a distinctly different and earlier surface. To prove this truncation, it is necessary to show that remnants of the early land form, which lie below the Perris surface, are erosional depressions rather than down-faulted segments, and that they could only have been formed earlier than the Perris surface.

The bedrock floor under Arlington Valley is believed by Menden-

[15] W. M. Davis, "The Peneplain," *Amer. Geol.*, Vol. XXIII (1899), p. 207; "Base-level, Grade and Peneplain," *Jour. Geol.*, Vol. X (1902), pp. 102–3; "Peneplains and the Geographical Cycle," *Geol. Soc. Amer. Bull. 33* (1922), pp. 587–89.

[16] J. H. Maxson and G. H. Anderson, "Terminology of Surface Forms of the Erosion Cycle," *Jour. Geol.*, Vol. XVIII (1935), p. 90.

hall[17] to be a down-faulted part of what is here called the Perris surface, the escarpment between the two being a fault scarp. However, there is substantial reason for believing that this scarp, which rises some 500 feet above the alluvium on Arlington Valley floor, is in reality merely an old erosional valley wall. First, there is no structural evidence indicating a fault along this line. Second, the irregular crescentic trace of the present scarp is very suggestive of an erosional origin. Third, the relief of the bedrock underlying Arlington Valley indicates that floor to be entirely different in topographic stage from the Perris surface which near by is of quite low relief. Not only does the buried floor have considerable relief, as proved by the height of the crystalline bosses which project through the alluvial cover, but well logs show the existence of a pronounced buried canyon which leads from Arlington northeasterly for several miles in a direction opposite to the present course of the nearby Santa Ana River.[18] It would appear, therefore, that Arlington Valley is a depression caused by normal erosion rather than a down-faulted portion of the Perris surface.

Similarly, it is reasonable to believe that the topographic scarp separating the bedrock floor of Elsinore trough from the Perris surface is erosional and that the two surfaces are not one and the same surface merely dislocated. While indisputable faulting of the valley floor has produced a graben[19] which occupies a portion of the Elsinore trough, the nearest side of the graben has no relation to the topographic scarp forming the northeast side of the trough (Fig. 4). This topographic scarp, furthermore, has the irregularity of an erosional feature, and near Corona swings around to join the erosional scarp separating Arlington Valley from the Perris surface (Fig. 2).

There are particularly good reasons for believing that the buried

[17] W. C. Mendenhall, "Hydrology of the San Bernardino Valley, California," *U.S. Geol. Surv. Water Supply Paper 142* (1905), p. 31.

[18] Eckis, *op. cit.*, p. 171.

[19] The depth and areal limits of this graben structure are not entirely certain. Well-log evidence from a point over the middle of the trough about a mile northeast of Temescal Hot Springs shows that crystalline bedrock was not reached after 3,400 feet of drilling. A mile northwest of Lake Elsinore and presumably over the graben, bedrock was encountered after drilling 927 feet. See Waring, *op. cit.*, pp. 70, 79; R. Engel, "Preliminary Notes on the Geology of Elsinore Valley," *Geol. Soc. Amer. Bull. 39* (1928), abst., p. 267.

valley floors of the eastern half of the block are not a part of the Perris surface. First, it is not likely that they are a down-faulted segment of the Perris surface, because evidence, previously mentioned, has shown that important dislocation in the northeastern portion of the block is probably absent. Well-log evidence shows that these buried valleys represent a northeasterly sloping surface which emerges near the center of the block to intersect the Perris surface (Figs. 3 and 5). There is generally no prominent topographic scarp between these intersecting surfaces, such as that which separates Arlington Valley and Elsinore trough from the Perris surface, because of their low angle of intersection and because the alluvium buries the valley floors nearly to the level of the Perris surface. The depth of the buried valley floors gradually increases toward the northeastern margin of the block where, finally, their bedrock elevation is comparable with that of the bedrock floor in Arlington Valley and Elsinore trough, which is commonly 500–1,200 feet below the Perris surface. Second, well-log evidence shows that the relief of the buried bedrock valleys is considerably greater than that of the Perris surface; and, as a result, it indicates that the two are different surfaces. The third indication that the two surfaces are not one and the same is the existence of traces of the Perris surface, represented by rock-cut benches, on certain of the peaks protruding up from the bedrock through the sedimentary cover of the eastern half of the block. The monadnock-like peaks in this section, several of which exhibit these sporadic rock-cut benches at slight distances above the sedimentary cover, consequently must have existed before the development of the Perris surface and thus are portions of the early land form. For this reason, although they formed virtual monadnocks on the Perris datum plane, they are not true monadnocks developed by Perris baseleveling.

It is fairly certain that erosional incisions with the depth of the Arlington Valley floor, the unfaulted bedrock floor of Elsinore trough, and the buried valley floors of the eastern half of the block could not have been cut after the formation of the Perris surface, or the latter would have been destroyed. Therefore, it appears that such depressions must have antedated formation of the Perris surface. Consequently, these valleys must have been buried up to that datum plane when the Perris surface was cut.

GAVILAN-LAKEVIEW PENEPLAIN

The Gavilan region (Fig. 6) in the western portion of the Perris block and the top of the Lakeview Mountains (Fig. 7) in the eastern portion of the block are old erosional surfaces of low relief. The surfaces in these two separated regions have the same elevation, approximately 2,100 feet above sea-level and some 400 feet above the average level of the Perris surface. Each region possesses scattered monadnocks, some of which are very symmetrical and emphasize the physiographic incongruity of these high base levels by occurring on their periphery overlooking the Perris surface below.

Since the surface in the Gavilan region and that on the top of the Lakeview Mountains, which are some 15 miles away, coincide in elevation, they are assumed to represent segments of an original extensive erosional surface of low relief. For convenience this surface will henceforth be called the "Gavilan-Lakeview peneplain." The imprint of this horizontal erosional surface, like that of the Perris surface, thus is to be seen on the crystalline rocks of both the western and eastern portions of the block.

RELATION OF THE GAVILAN-LAKEVIEW PENEPLAIN TO THE PERRIS SURFACE

When the old erosional surfaces in the Gavilan and Lakeview mountains were seen, the question arose as to whether they were not portions of the Perris surface raised to their present position by faulting.

R. T. Hill[20] has expressed the opinion that the Lakeview Mountains, as well as the other smaller monadnock-like masses in this vicinity, are residuals of a former up-faulted strip running through this portion of the Perris block. He also postulates numerous cross rifts in this eroded fault strip. Similarly, W. J. Miller[21] has resorted to a complicated system of fault blocks in an effort to explain discordant old erosion surfaces in equivalent crystalline rocks of San Diego County, not far distant. In the same county, around Warner's

[20] *Op. cit.*, p. 168.

[21] "Geologic Section across the Peninsular Mountains of Southern California," *Geol. Soc. Amer., 32d Ann. Meeting, Cordilleran Sect.* (1933), abst.

FIG. 6.—The old erosional surface in the Gavilan region as seen looking north toward Gavilan Peak, which is a monadnock.

FIG. 7.—The old erosional surface at the top of the Lakeview Mountains, as seen looking southeast across Juniper Flats.

Hot Springs, Sauer[22] not only employs complex faulting to explain discordant old erosion surfaces but believes that, in his particular area, such surfaces are often *primärrümpfe*, as defined by Penck, rather than portions of a normal upraised peneplain.

The old-age surface found in the Gavilan region is not a portion of the Perris surface elevated by faulting. This is proved by field mapping, which shows an absence of bedrock dislocation. The Gavilan region (Fig. 8) now represents merely the surface of truncation along which the top of a very large monadnock on the Perris surface was removed.

FIG. 8.—View southwest from a monadnock on the Perris surface in the northwestern part of the block, showing the surface of truncation in the Gavilan region. The Elsinore trough and Santa Ana Mountains lie in the far distant background.

Similarly, there is no faulting along which the surface forming the top of the Lakeview Mountains could have been raised from the rock-cut bench which occurs near their base on the northwest side and which is in all probability part of the Perris surface. The heavy sedimentary cover around the rest of the base of the Lakeview Mountains (Fig. 9), however, prevents direct disproval of the existence of surrounding faults. However, the unusually close coincidence in the elevation and attitude of the flattened top of the Lakeview Mountains with the old-age surface in the Gavilan region is

[22] C. Sauer, "Land Forms in the Peninsular Range of California as Developed about Warner's Hot Springs and Mesa Grande," *Univ. Calif. Publ. in Geog.*, Vol. III (1929), pp. 199–290.

good reason for believing that the former was coeval with the Gavilan surface and is not an up-faulted portion of the Perris surface. The surface at the top of the Lakeview Mountains consequently represents the plane of truncation incised across a large monadnock-like mass which was not cut away during formation of the Perris surface.

While the foregoing is satisfactory proof that the surfaces in the Gavilan region and Lakeview Mountains are not a portion of the

FIG. 9.—View toward the southeast side of the Lakeview Mountains showing their truncated top. The sedimentary cover, which buries the early land form in this particular vicinity, appears in the foreground.

Perris surface, it does not tell whether the Lakeview Mountains are a truncated monadnock-like mass or an upraised fault block which has been truncated. Dislocation of drainage lines and rift features suggest that the small mountain mass called Box Springs Mountains, which lies on the north edge of the Perris block, has been raised by local faulting which is more or less parallel and probably related to the San Jacinto rift. Also, the previously mentioned fact that the alluvium covering the Perris block 3 miles north of the northern tip of the Lakeview Mountains has a depth greater than 1,500 feet[23] suggests downward dislocation in the block at this locality. Yet, outside of these instances, it would seem that faulting between the

[23] Waring, *op. cit.*, p. 43.

monadnock-like masses in the northeastern, partially buried section of the Perris block is largely absent for the reasons given under the discussion of the areal geology and structure of the block. Consequently, it is probable that the Lakeview Mountains represent a protruding portion of the early land form which has been truncated and not an upraised fault block which has been beveled.

SUPERPOSED DRAINAGE OF THE PERRIS BLOCK

There are two clear examples of superposed drainage located in the southern portion of the Perris block along the course of the San Jacinto River. The first of these (Fig. 2, *S1*) is Railroad Canyon and the other (*S2*), 3 miles southwest, is the canyon through which the San Jacinto River flows to join Lake Elsinore. These canyons, cut through unfaulted crystalline ridges which are practically monadnocks on the margin of the Perris surface, indicate that the course of ancient San Jacinto River was established at these two points by superposition after the Perris surface was cut. Consequently, the Perris surface and the monadnocks thereon must have been buried to a depth consistent with the tops of the canyons.

There are three other instances of superposed drainage occurring in the early-land-form valley wall carved on the southwest side of the Perris block. They are represented by the re-entrant canyons of Temescal Creek near Alberhill (*S3*), Lee Lake (*S4*), and Corona (*S5*). Field investigation has shown that these canyons are cut back from the Elsinore trough into the unfaulted bedrock of the Perris block northeast of the graben. After recognizing the unusual nature of these canyons, the question arises as to whether they are superposed or antecedent.

It is possible that the canyons considered here might be antecedent under appropriate circumstances. The fault delineating the Perris block on the southwest runs more or less parallel to the line connecting the three canyons. If ancient Temescal Creek had been a stream which meandered across this fault line and was able to entrench a portion of its course on the borders of the Perris block as fast as the latter rose, the present canyons could have been cut in antecedent fashion.

Available evidence, however, points to the superposed nature of the canyons. First, the valley wall in which these canyons are cut

has been proved an old erosional wall. The old crystalline valley floor extends out from this wall (Fig. 2) until it is cut off by the fault forming the near side of the graben. If the ancient stream in the old valley floor had started to entrench meanders on the Perris block side of this fault, it would have started at this valley-floor level rather than high up in the side of the valley wall. Second, the indubitably superposed drainage at Railroad Canyon, as well as the existence of the Gavilan-Lakeview peneplain, indicate burial of the Perris surface. Consequently, the bedrock Elsinore Valley, which lay below the Perris surface, likewise must have been buried with sediments. This burial of the Elsinore trough, plus the known superposition of nearby drainage, makes it logical to conclude that the three canyons in the valley wall along the trough were formed also by a superposed, rather than an antecedent, stream.

BURIAL AND EXHUMATION OF THE PERRIS BLOCK

It has been shown that the Perris surface was formed later than the buried valley floors in the eastern half of the block and the Arlington and Elsinore depressions which border the block, because it truncates their valley walls. Such a surface could have been cut above the valley floors only if the latter were buried.

It is probable that the sediments which originally partially buried the early land form in the eastern half of the Perris block and permitting cutting of the Perris surface were early facies of the San Jacinto series. As has been stated previously, these deposits range from Lower Pliocene to mid-Pleistocene in age. Sandstones and shales of the series visibly protrude through the alluvial cover at Casa Loma and Park Hill, near the eastern corner of the block. Farther south, along Bautista Creek, which is just outside of the area under consideration, the actual depositional contact of these continental sediments with the underlying crystalline basement complex can be seen. There is good reason, consequently, for believing that San Jacinto sediments lie between much of the surface alluvium and the buried bedrock valley floors in the eastern half of the block.

The sediments which filled Arlington Valley and Elsinore trough up to the level of the Perris surface are not easily ascertainable because the upper portions of these bedrock depressions are now largely

exhumed. In Elsinore trough, the Alberhill clays directly overlie the bedrock floor and can be seen to have constituted formerly a considerable portion of this filling. Near Corona appear Miocene sediments which may have been involved in filling the Elsinore trough as well as Arlington Valley. It is possible, also, that the San Jacinto sediments may have extended throughout these depressions and formed the upper portion of the sedimentary blanket which permitted Perris baseleveling.

The Gavilan-Lakeview peneplain must have been formed later than the Perris surface, because it truncates both a large monadnock on the Perris surface and a large monadnock-like mass projecting from the partially buried early land form through the Perris datum plane. The only way in which this baselevel could have been formed was by burial of the Perris surface and the truncated valleys of the early land form with sediments.

It is fairly certain that the San Jacinto sediments were responsible for this renewed burial of the block. The reason for this is the probable abundance of these sediments under the alluvium of the eastern half of the block, their visible abundance on the borders of this region, and the absence of other sediments near by which might serve as a sedimentary blanket.

After completion of the Gavilan-Lakeview peneplain, a change of baselevel for this region resulted in a rejuvenated erosion which today has stripped away most of the sediments covering the block and has laid bare the crystalline remnants of the Gavilan-Lakeview peneplain and the Perris surface, and part of the early land form. Thus the visible basement complex of the Perris block, at least below the Gavilan-Lakeview peneplain, represents an exhumed surface. The Perris surface, in particular, is much like some of the exhumed old erosion surfaces described in New Zealand.[24] The former existence of the sedimentary cover of the block is corroborated, of course, by the superposed canyons which are cut through the monadnocks on the Perris surface and into the old valley wall of Elsinore trough.

PHYSIOGRAPHIC HISTORY OF THE PERRIS BLOCK

The buried valley floors in the eastern half of the block, as well as the valley walls and crystalline floors cut into the Perris block

[24] C. A. Cotton, *Geomorphology of New Zealand* (1922), pp. 131–50.

along Arlington Valley and the Elsinore trough, are remnants of the early land form. They have been shown to be older than the Perris surface, and they represent the oldest surface on the block. These remnants of the early land form are cut into schists of the Triassic Elsinore series and the hypabyssal and various plutonic rocks which are known to have intruded the schists probably toward the close of the Jurassic. At several localities along the Elsinore trough, notably at Alberhill, the Alberhill clays lie upon the sloping surface of the old valley wall. Consequently, incision of the early land form to its present depths in the crystalline complex was initiated probably after the Jurassic and was completed in time for deposition of the Alberhill clays in the lower Eocene (Martinez).

The Perris surface could have been cut only after burial of the surrounding valleys. Since the Alberhill clays are the earliest known sediments to bury any portion of the early land form, the Perris surface was not incised until after the Eocene (Martinez). The buried valley floors of the early land form in the eastern half of the block, however, almost certainly are overlain by portions of the Lower Pliocene to mid-Pleistocene San Jacinto sediments. This evidence is sufficient to show that, while the Alberhill clays may have been a factor in the burial of the block, the Perris surface probably was not cut until after the early Pliocene. It was completed, of course, before the formation of the Gavilan-Lakeview peneplain, since the latter truncates a large monadnock (the Gavilan region) on the Perris surface and a monadnock-like mass (the Lakeview Mountains) which protruded through the Perris datum plane.

While there is little question on the relative age of the Perris surface and the Gavilan-Lakeview peneplain, there is no evidence on the latest age limit of the latter. The San Jacinto sediments, again, were undoubtedly responsible for burial of the block up to the level at which the Gavilan-Lakeview peneplain was cut, but actual cutting may have taken place later than the youngest San Jacinto sediments. The time for stripping the Perris block to its present stage of exhumation suggests, however, that the Gavilan-Lakeview peneplain was completed at least by the date of the latest San Jacinto sediments, the mid-Pleistocene.

When exhumation of the Perris block was commenced, probably in the Pleistocene, it is likely that the normal drainage in this region

was toward the southwest. This is substantiated by the present courses of the Santa Ana and the Santa Margarita rivers, which lie on either side of the area under consideration and which are antecedent streams whose age, without much doubt, extends back to the initiation of this exhumation. It is quite probable that the five instances of superposed drainage on the Perris block were developed simultaneously and that the ancient San Jacinto River, cutting what is now Railroad Canyon, continued its southwest course to the ocean. Whether ancient Temescal Creek was a tributary of the Santa Ana River or the Santa Jacinto River cannot be told.

Sometime after this early drainage was established, there was initiated the fault along which the present Santa Ana Mountains rose. While the Santa Ana and Santa Margarita rivers were able to cut through this barrier as it rose across their path, San Jacinto River was blocked, probably to form what is now Lake Elsinore. Eventually it found a lateral outlet along the entrenched course of Temescal Creek, which enabled it to flow into the Santa Ana River.

There exists a probability that the fault along which the Santa Ana Mountains rose and the roughly parallel fault which forms the northeastern side of the Elsinore graben were contemporaneous. It is fairly certain that down-dropping of the segment between the two faults proceeded at a rate no greater than the downward entrenchment of ancient Temescal Creek into the three locations of superposition. If the down-dropping had been rapid, these canyons obviously would have been abandoned in favor of a course completely within the graben. It may be that the early movement on the faulted wedge was upward rather than downward, and that it, rather than the Santa Ana Mountains block, was directly responsible for blocking the course of ancient San Jacinto River. If so, there has been a later reversal of movement, for the wedge now forms the bottom of a buried graben. Finally, the progressive elevation of the Santa Ana Mountains has resulted in strong alluvial fans which have continually pushed the present Temescal Creek against the northeast side of the trough and which have been of material aid in keeping it at work within the superposed canyons.

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THE EFFECT OF MIOCENE LAVAS ON THE COURSE OF COLUMBIA RIVER IN CENTRAL WASHINGTON

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ABSTRACT

Earlier work has indicated that between the Spokane River and Wenatchee the plateau-marginal course of the Columbia River was determined by northerly and northwesterly advancing flows of lava. In entering the Columbia Plateau at Wenatchee, the river is shown to have been influenced by floods of lava from the west.

INTRODUCTION

After crossing the Canadian boundary the Columbia River flows in a southerly course to its junction with the Spokane. Here it turns abruptly west and as far as Wenatchee in central Washington the Columbia Valley closely approximates the sharp line of demarcation between the lava-covered Columbia Plateau and the bordering highlands of older rocks. At Wenatchee the river abandons this marginal course and turns southeastward into the basaltic plateau.

In an early report Bailey Willis suggested that the abrupt westward turn of the river at the mouth of the Spokane and its marginal relation to the lava plateau was determined by the junction line of flows from both the north and south, the line of least elevation of the cooled surface having lain near the edge.[1] He further noted the centripetal relation of the Columbia tributaries from the bordering highlands—Wenatchee, Methow, Okanogan, and Sanpoil rivers—to the center of the plateau. This fact, together with the more advanced development of the tributaries, suggested to him that the older Columbia Valley is buried beneath the lavas of the plateau.

Later work in central Washington confirms Willis' theory that the course of the Columbia is a response to advancing flows of lava. Not only is this true of that part of its course which follows the border of the lava field, between the mouth of Spokane River and the city of

[1] Bailey Willis, "Changes in River Courses in Washington Territory Due to Glaciation," *U.S. Geol. Surv. Bull. 40* (1887), p. 7.

Wenatchee, but new evidence indicates that in entering the plateau at Wenatchee the Columbia continued to be governed by the initial topography created at the time of extrusion of the basalt.

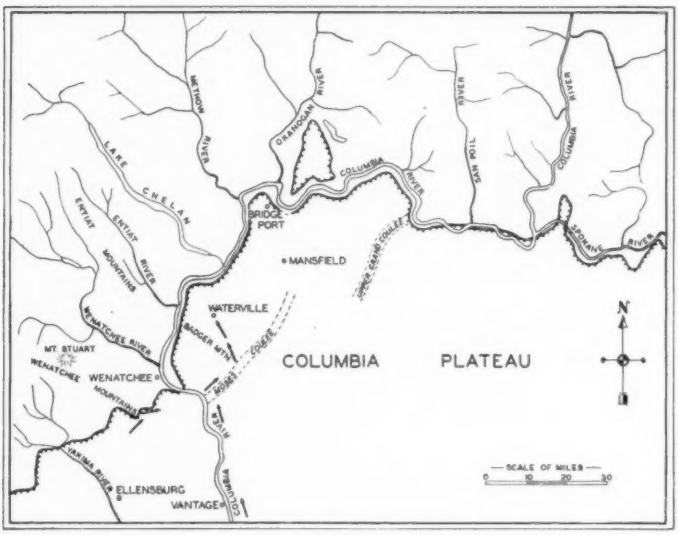

FIG. 1.—Index map of central Washington showing the Columbia River, its chief tributaries, and the border of the lava field (dashed line). Various outliers beyond the main lava border, particularly southwest of Wenatchee and between Okanogan River and the upper Columbia, are omitted. Arrows show the direction of lava advance as indicated by foreset beds in palagonite tuffs and breccias.

SEDIMENTARY INTERCALATIONS ALONG THE PLATEAU BORDER

According to Willis' theory, the marginal course of the Columbia between the Spokane River and the city of Wenatchee indicated that the main flood of lava came from the south. Since the older Columbia Valley seems to be buried beneath the basalts, the result of flows advancing up-valley could have had but one effect—the damming of the waters of the tributaries to form successive marginal lakes in which sediments would be deposited. There are abundant records of such sediments.

I. C. Russell reported that wells near Waterville, after passing

through the first 40 to 50 feet of basalt, encounter 25 to 30 feet of sand and clay, beneath which there is more basalt.[2] A. C. Waters states that in the same vicinity, along the border of Columbia Canyon, there are layers of interbedded sediments up to 70 feet in thickness. A well at Waterville encountered four layers of interbedded sediments between depths of 400 and 770 feet. The main mineral constituents of these sands were derived from the nearby Swakane gneiss and Chelan granodiorite.[3] Henry Landes has stated to the writer that several beds of sediment with a maximum thickness of 6 feet were encountered in drilling on the site of the Rock Island Power Plant about 12 miles below Wenatchee. In lower Douglas Creek, a tributary of Moses Coulee from the north, R. E. Fuller has described the occurrence of sediments which were disrupted and partially incorporated by advancing lavas.[4] At the new Gingko State Park, between Ellensburg and Vantage, the writer has noted a 15-foot layer of light feldspathic sandstone and conglomerate beneath the fossil-tree horizon. In the latter, the prevalence of yellow palagonite in the brecciated lavas indicates that the flows entered a small lake. The trees probably escaped burning because of a waterlogged condition.

The locations cited are within comparatively short distances of the western border of the plateau. Similar conditions are known to have prevailed on the eastern and northern margins. I. C. Russell first recorded the occurrence of lake beds about the border of the plateau and stated his belief "that, in eastern Washington at least, the lava sheets flowed toward the mountains, and on congealing dammed their drainage streams."[5] Pardee and Bryan describe lavas interbedded with sediments in the vicinity of Spokane.[6] In a study of the

[2] I. C. Russell, "A Geological Reconnaissance in Central Washington," *U.S. Geol. Surv. Bull. 108* (1893), p. 85.

[3] A. C. Waters, "Geology of the Southern Half of the Chelan Quadrangle, Washington," Yale University Doctorate Thesis (1930).

[4] R. E. Fuller, "The Aqueous Chilling of Basaltic Lava on the Columbia River Plateau," *Am. Jour. Sci.*, Vol. XXI (1931), pp. 294–300.

[5] I. C. Russell, "A Reconnaissance in Southeastern Washington," *U.S. Geol. Surv. Water Supply and Irrigation Paper 4* (1897), p. 55.

[6] J. T. Pardee and Kirk Bryan, "Geology of the Latah Formation in Relation to the Lavas of the Columbia Plateau near Spokane, Washington," *U. S. Geol. Surv. Prof. Paper 140-A* (1926), pp. 1–16.

Latah formation of Idaho, Kirkham and Johnson report having visited 40 different localities, many of them previously mentioned in the literature, where sediments are interstratified with lavas.[7] They concurred in Russell's theory of origin. Plant-bearing clays outcrop at the north end of Grand Coulee where it descends abruptly to the Columbia.[8] Sediments occur within the lavas of northern Douglas County at Bridgeport and northwest of Mansfield.[9]

FORESET BEDDING IN PALAGONITE TUFFS AND BRECCIAS

R. E. Fuller has described the effects of lava flows entering bodies of water near the western border of the Columbia Plateau.[10] Several excellent exposures in the vicinity of lower Moses Coulee and Columbia Valley near Vantage reveal ellipsoidal lavas, breccias of basalt and glassy sideromelane, together with tuffs and breccias of palagonite, an alteration product of the former. Inclined beds not unlike delta foresets are shown to have resulted when highly fluid streams of lava were chilled and granulated on advancing into bodies of water. The predominant northerly inclination of such foreset beds indicate that the flows of lava came from the south. In one locality, however, on the north wall of Moses Coulee about 4 miles from its mouth, a photograph by Fuller indicates a more westerly source of the lavas.[11] Foreset-bedded palagonite indicating northwesterly advance of the lava flows is well exposed in a quarry $1\frac{1}{2}$ miles southeast of Waterville, and the road cuts on the Sunset Highway between Waterville and Douglas reveal intercalations of palagonite breccia, pillow lavas, and thin layers of sediment in the normal basaltic series.[12] Although palagonite tuffs and breccias as well as pillow lavas are to be found in numerous localities in the general vicinity, foreset bedding is not always apparent.

During the course of geologic mapping of the Wenatchee Quadrangle, the writer encountered two important localities where lava

[7] V. R. D. Kirkham and M. M. Johnson, "The Latah Formation in Idaho," *Jour. Geol.*, Vol. XXXVII (1929), pp. 483–504.

[8] E. W. Berry, "A Miocene Flora from Grand Coulee, Washington," *U.S. Geol. Surv. Prof. Paper 170-C* (1931), pp. 31–42.

[9] A. C. Waters, personal communication.

[10] *Op. cit.* [11] *Op. cit.*, p. 290. [12] A. C. Waters, personal communication.

flows entered bodies of water. The first of these is located along the east and northeast margins of Wenatchee Heights, the broad divide area between Squillchuck and Stemilt canyons, 4 miles south of Wenatchee. Nine hundred feet above the Columbia River, at the mouth of a deep ravine on the southwest bluff, steeply dipping sandstones of the early Eocene Swauk formation are overlain unconformably by a boulder conglomerate almost entirely of basalt. This

FIG. 2.—Foreset-bedded palagonite breccia in the east wall of Columbia Valley, about 3 miles south of Moses Coulee. The height of the exposure is approximately 125 feet.

conglomerate is approximately 30 feet thick and has an imperfect horizontal stratification. Basalt breccia with a matrix of palagonite tuff occurs at the top of the exposure. The upper 500 feet of the bluff are made up of poorly exposed lavas. This locality is 8 miles east of the westernmost divide remnant of the cover of basalt which formerly overlay the region south of Wenatchee. Since the larger boulders of the poorly stratified conglomerate average 1 foot in diameter, it is evident that they were laid down in a rapid current of water. The fact that this outcrop occurs on a bluff of the Columbia

Valley and that after post-Miocene erosion it is still overlain by 500 feet of basalt seems highly significant. It suggests that locally the Columbia was established in nearly its present course long before eruptions had ceased. Another exposure in this same locality occurs near the top of the high west bluff of Stemilt Creek, near the center of Section 25, T. 22 N., R. 20 E., where a crescentic landslide scar exposes 125 feet of interstratified palagonite tuffs, basalt breccia, sediments, and finger-like flows of lava.

A second locality for the occurrence of large outcrops of palagonite tuffs and breccias is on the summit of the Wenatchee Mountains near the headwaters of Squillchuck Creek and about 2 miles southeast of Mission Peak (Old Baldy). In the southwestern part of Section 26, T. 21 N., R. 19 E., on the north slope of the range, the higher portion of a steep cliff of palagonite breccias shows foreset bedding which dips eastward, indicating that a body of water was entered by flows of lava from the west. An outcrop in the same palagonite horizon, but located on the south side of the summit, has foresets which are inclined toward the northeast. West of Old Baldy numerous dikes cut the Eocene Swauk formation and on the slopes of the range south of Mount Stuart a remarkable swarm of dikes has been mapped.[13] G. O. Smith noted that certain of these dikes connect with the middle Eocene Teanaway basaltic flows; in the western portion of the Wenatchee Quadrangle, however, the writer has observed a multiple basaltic dike in the eastern part of the swarm, the earlier member of which is coarser in texture and slightly more altered than the later one, suggesting a time interval between the respective intrusions. At a locality about 20 miles west of Ellensburg, large dikes and some intrusive bodies of diabase are shown by Smith to be genetically related to flows of Yakima basalt (Miocene).[14] Whether the lavas were erupted from the vicinity of the dike swarm or in the region west of Ellensburg, the inclination of foreset beds in the palagonite tuffs and breccias of the Wenatchee Mountains indicates that the area south of Mount Stuart was a source of these easterly directed flows of Miocene basalt.

[13] G. O. Smith, "Mount Stuart Folio," *U.S. Geol. Surv. Folio 106* (1904).

[14] *Ibid.*, p. 8.

INTERPRETATION AND CONCLUSIONS

Waters found no dikes of the Columbia River lavas in the Chelan Quadrangle. The various instances of sedimentary and palagonitic intercalations, together with the evidence of foreset beds in the Moses Coulee localities, led him to support the earlier ideas of Willis. Waters says:

> Since the lava flows advanced from the interior of the plateau toward its margins, the surface of the flows at the cessation of eruptions must have sloped toward the margins of the lava field. On the other hand the gneissic highlands to the west sloped toward the plateau. The junction line of these two diverse areas then would be lower than any part of the surrounding topography. The writer believes that this fact accounts for the present position of Columbia River, which, from the point where it first encounters the Columbia River basalt in its journey through the State, marks out with extreme nicety the western and northern border of the basaltic plateau until it plunges into the area of lavas a few miles south of Wenatchee.[15]

To account for this peculiar southeastward turn of the Columbia at Wenatchee, two hypotheses have been considered: (1) that the river once continued along the lava border south of Wenatchee but was diverted from this course by anticlinal warping of the Wenatchee Mountains; and (2) that the Columbia remained in the course determined when the lavas were erupted. The fact that the river detours to the east of the Wenatchee Mountains seems to favor the first of these hypotheses. However, other similar ranges, the Entiat-Badger Mountains and Saddle Mountain of the eastern Cascades, are crossed antecedently by the Columbia. It seems that the real test of the theory consists in the presence or absence of remnants of a prediversion valley south of Wenatchee. No indications of such a valley have been found. Furthermore, at the point where the Columbia River enters a 2000-foot box canyon 10 miles below Wenatchee the lavas are moderately inclined to the northeast. If the river had been diverted by warping it should now approximate the synclinal axis between the Wenatchee and Badger anticlines. This local antecedency is inconsistent with the idea of deflection by uplift.

The fact that near Wenatchee a horizontally stratified bed of basalt conglomerate occurs on a bluff of the Columbia at least

[15] *Op. cit.*

8 miles east of the original basalt border—and that this conglomerate is still, after post-Miocene erosion, overlain by 500 feet of lava—suggests that locally the Columbia River was established in essentially its present course long before eruptions ceased. The presence of easterly dipping foreset beds in palagonite tuffs and breccias of the Wenatchee Mountains, together with the numerous dikes which occur south and east of Mount Stuart, are regarded as convincing evidence that the southeastward deflection of the Columbia River into the plateau at Wenatchee was in direct response to floods of basalt, the river following the junction line between the easterly advancing lavas erupted from the vicinity of the western margin and the main body of the basalt series from within the plateau.

ACKNOWLEDGMENT.—The writer gratefully acknowledges the helpful criticisms of the manuscript by G. E. Goodspeed, C. E. Weaver, R. E. Fuller of the University of Washington, and A. C. Waters of Stanford University. In particular, he expresses his gratitude to Dr. Waters for additional significant data.

VERTICAL MOVEMENTS OF EARTH'S CRUST AS DETERMINED BY LEVELING

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ABSTRACT

The leveling net which has been extended over the country to serve many engineering purposes is used also to detect vertical movements in the earth's crust by re-running, at intervals, the lines in the net and comparing the results of the different runnings. In certain critical areas in California a number of the lines have been re-run, but so far the only area in which large changes have been found is in San Jose and vicinity.

The leveling net which has been extended over the United States as a basis for mapping and other engineering work furnishes results of great value to the geologist and geophysicist as well as to the engineer. There is no question but that great vertical movements have occurred in the crust of the earth. This is indicated by the presence of marine fossils at great elevations in mountain areas. There are very few parts of the earth's surface that have not been below sea-level one or more times during geological time. Areas where there were mountains in earlier geological times are now at or below sea-level. The rate of movement is uncertain and usually slow, and it is very difficult at present to determine whether points on the surface of the earth are being maintained in their present elevations or are going up or down. Of course, when an earthquake occurs with a rift in the surface, one can tell with certainty that vertical movements have taken place recently.

For many years the Coast and Geodetic Survey and some other branches of the government have been extending a great network of lines of levels over this country. There are many uses for leveling data. The corps of engineers of the army has as one of its principal duties the development of rivers for navigation and the prevention of floods. For this work elevations are needed and lines of levels are therefore run along these rivers to supply the essential data.

The Coast and Geodetic Survey, in extending its triangulation,

needs elevations of base lines in order to determine the lengths of those lines referred to sea-level. The United States Geological Survey needs elevations for the contouring of its topographic maps. All of the agencies at the beginning of their work operated more or less independently in determining elevations of bench marks. Eventually, many of the lines of the several organizations were joined and an adjustment of the combined lines was made to furnish the most probable elevations of the bench marks. The first adjustment was made in 1898. Since that time there have been other adjustments. The last one was in 1929, when the leveling net of the country comprised 55,000 miles of lines of first-order levels.

Since 1929 the leveling net has been very greatly extended. There are now approximately 260,000 miles of lines of levels covering the country like a great fish net, with the meshes approximately 25 miles across except for a part of the mountain areas of the West. The 25-mile spacing of the entire leveling net is the present objective.

This net of lines of first- and second-order leveling with the 25-mile spacing furnishes the framework for the detailed leveling that must be done for controlling topographic mapping and for many other engineering operations. It is generally held that for the topographic control the lines of levels should be spaced at intervals of 5 or 6 miles. It is readily seen that the detailed work within the 25-mile meshes can be easily fitted to the principal lines of the net.

In the leveling net the lines of first order have been run at intervals of approximately 100 miles. Within each one of the 100-mile meshes the leveling has been of second-order accuracy. In first-order leveling a line is run in both directions. The line is divided into sections varying in length but averaging between 1,000 and 1,600 meters. If the two runnings of a section do not agree within 4 millimeters times the square root of the distance in kilometers, the section is re-run in order to obtain two runnings in opposite directions that do agree within that limit. For a section one kilometer in length, for example, the difference allowable is 4 millimeters, and for a distance of 1.6 kilometers it is approximately 5 millimeters.

The best measure of the accuracy of leveling is the rate of correction required per unit length in order to close circuits. In general, for first-order work this correction is seldom greater than 0.5 millimeter

per kilometer. The average correction is less than 0.2 millimeter per kilometer.

The first-order leveling by the Coast and Geodetic Survey is run with a special instrument designed by E. G. Fischer who was, for many years, in charge of the Instrument Division of this Bureau. In recent years a leveling rod of special design, having an invar strip in its face that carries the graduations in centimeters, has been used. This invar strip is rigidly attached to a steel foot at the bottom of the

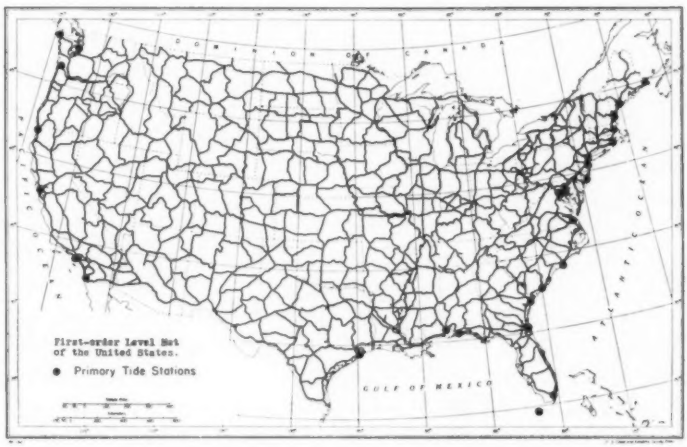

FIG. 1.—First-order level net of the United States

rod and is supported by the wooden part of the rod on which are indicated the meters and decimeters. All measurements are made in the metric system.

On the second-order leveling, which lies within the 100-mile meshes of the net, the lines are run in only one direction unless the leveling involved in a loop fails to close within certain prescribed limits. If the closing error is beyond the limit, the lines are run a second time. Exactly the same instruments and methods are employed on the second-order leveling as on the first-order work except as regards the number of runnings of the sections. Necessarily, the closing errors are larger in second-order work than in first. That is

partly because the second-order line must be fitted into the previously adjusted first-order leveling. However, it is very seldom that the correction per kilometer on the second-order work is greater than 1 millimeter per kilometer of the distance run.

Even the second-order leveling is quite accurate enough for testing the stability of the ground in earthquake areas or in regions of limited extent where earthquakes may be anticipated.

With the level net of our country so widespread and with lines so closely spaced, it will be possible in the future to determine whether elevations of bench marks are changing or not. All that will be needed will be to re-run any line of levels and make a comparison of the elevations determined by the two or more runnings.

Some lines of levels have already been re-run in parts of California to determine the amount of change in elevation, if any, in regions where instability has been suspected or where an earthquake has occurred. So far the only area in which large changes have been found is in San Jose and vicinity. Lines of levels were extended through San Jose in 1912 and 1920, and these were re-run in 1932. The 1932 leveling showed changes in elevations as great as 3 feet. No earthquake had occurred in this region between 1920 and 1932.

The leveling in 1920 consisted merely of starting a line from two or more bench marks established in 1912. The differences in elevation found in 1920 agreed closely with those determined in 1912. Had any movement of the ground occurred between those dates it must have affected the elevations of the several bench marks by very nearly the same amount.

There has been some discussion as to whether the changes are due to tectonic movements or to a settlement of the ground because of excessive pumping of underground waters. Although the explanation of the change is not known to the officials of the Coast and Geodetic Survey, they have been much interested in the San Jose area and have extended over it a network of lines of levels with a view to determining the limits of the affected area.

The leveling in the vicinity of San Jose has been repeated several times and there are evidences of a continuous subsidence. It is not known whether or not the rate of subsidence is exactly uniform.

Tiltmeters have been used in Japan to test the stability of areas in

which earthquakes are expected. At times these tiltmeters have shown such rapid changes in slope that earthquakes were predicted within a short time and people moved away from certain villages that were located on the shores in the immediate vicinity. In one case, at least, the earthquake came shortly after the evacuation and many lives were undoubtedly saved.

It is not known whether an earthquake is caused by regional or local forces. If the former, then presumably after an earthquake has occurred there would be changes in elevation of the leveling bench marks over a great area surrounding the epicenter of the quake. If the causes are local only a small area would show these changes. This is a matter of great importance to geologists, and it is hoped that in the future lines of levels may be re-run after earthquakes in the areas surrounding the epicenters. Of course, a small quake may make no changes in elevations, but enough earthquakes of sizeable proportions do occur to make it possible in the way outlined above to attack the problem as to whether the quakes are regional or local.

In any areas where earthquakes are anticipated the lines of levels for the area can be re-run at such intervals as may appear desirable. This interval may be five or some other number of years. Repeated re-runnings of the lines should show, after a few years, whether there are being set up in the crust below an area strains which are changing the surface configuration. Of course, such changes are likely to be small prior to the earthquake. Whether they would be measured in feet or inches no one could tell until several lines of levels had been re-run at intervals of a few years.

The Coast and Geodetic Survey has been co-operating during the past ten years or more with the Committee in Seismology of the Carnegie Institution of Washington. The work of the Survey has consisted partly in re-observing the angles of triangles in Nevada and California and in re-running certain lines of levels. The most important work, however, has been the execution of special arcs of triangulation and lines of levels across some of the earthquake zones of California. For these arcs and lines the stations and bench marks have been very closely spaced.

Much has been written on the stability or instability of the continental coasts as indicated by shell mounds, stumps of trees, and

other evidences of changes in elevation. It is rather remarkable, though, that different interpretations are placed upon the phenomena observed. A paper by Richard P. Goldthwait, entitled "The Damariscotta Shell Heaps and Coastal Stability," which appeared in the July, 1935, number of the *American Journal of Science*, gives a number of references to articles dealing with the stability or instability of coast lines.

There is one very sure way of determining whether the land adjacent to the coast is stable or not. It is to have a long series of tidal observations on tide gauges connected by accurate leveling to the national leveling net. There are now thirty-four so-called primary tide stations along the shores of this country, and there are many other places along the coasts at which tidal observations have been made for at least a few months. Most of the primary and many of the other tidal stations already have been connected with the leveling net.

If the tidal observations through a number of years indicate a change in mean sea-level with respect to the so-called tidal bench marks that are established near the tidal stations, a line of levels extending inland from the tidal stations should be re-run in order to learn whether the apparent change in elevation of the shore is only a local phenomenon or whether it is one involving a large area extending back from the shore. It is possible at times that harbor developments may affect the elevations of the tidal bench marks. However, it is very improbable that such developments would affect each one of several tidal bench marks by exactly the same amount. However, whenever any uncertainty exists as to the stability of the tidal bench marks, a line of levels extending inland from the tidal stations should be re-run and a comparison made of the elevations of the bench marks along the line for the two runnings.

Unfortunately, the tidal records of the Coast and Geodetic Survey that can be used in making tests of the stability of the coasts do not, with few exceptions, extend back many years. In the early years of the Coast and Geodetic Survey, tidal observations were considered to be of value only in reducing to some adopted plane of reference the soundings made to determine the depth of water. When the tidal records had served that purpose there was apparently no further use

for the tidal data. In consequence, there were very few primary tidal stations established and few permanent bench marks set to preserve the observed planes of reference. This situation has changed in recent years, for now at each one of the tidal stations, even those at which observations are made for only short periods, very substantial bench marks are set.

TABLE I

PORTLAND, MAINE

Year	Feet	Year	Feet
1912	13.08	1924	13.08
1913	13.03	1925	13.00
1914	13.09	1926	12.98
1915	13.17	1927	13.10
1916	13.13	1928	13.02
1917	13.14	1929	13.00
1918	13.14	1930	12.98
1919	13.23	1931	13.09
1920	13.19	1932	13.12
1921	13.14	1933	13.19
1922	13.02	1934	13.04
1923	13.07		

TABLE II

ATLANTIC CITY, NEW JERSEY

Year	Feet	Year	Feet
1912	6.01	1924	6.22
1913	6.08	1925	6.13
1914	6.20	1926	6.17
1915	6.26	1927	6.33
1916	6.17	1928	6.16
1917	6.18	1929	6.18
1918	6.23	1930	6.20
1919	6.37	1931	6.38
1920	6.31	1932	6.37
1921	6.32	1933	6.49
1922	6.22	1934	6.30
1923	6.19		

There are a few tidal stations at which continuous records have been made for a number of years and where substantial bench marks have been placed. This is notably the case for Portland, Maine; Atlantic City, New Jersey; Galveston, Texas; and San Francisco, California. Tables I–IV show the variation in sea-level in relation to

the bench marks, as determined by the tidal observations for different years. The values in feet are distances below one of the adjacent reference bench marks.

TABLE III

GALVESTON, TEXAS

Year	Feet	Year	Feet
1909	3.48	1922	3.72
1910	3.22	1923	3.78
1911	3.35	1924	3.50
1912	3.51	1925	3.48
1913	3.63	1926	3.50
1914	3.57	1927	3.78
1915	3.45	1928	3.58
1916	3.49	1929	3.99
1917	3.25	1930	3.69
1918	3.33	1931	3.49
1919	3.70	1932	3.73
1920	3.59	1933	3.91
1921	3.92	1934	3.63

TABLE IV

SAN FRANCISCO, CALIFORNIA

Year	Feet	Year	Feet
1898	8.30	1917	8.48
1899	8.44	1918	8.70
1900	8.50	1919	8.61
1901	8.46	1920	8.54
1902	8.57	1921	8.58
1903	8.53	1922	8.55
1904	8.63	1923	8.52
1905	8.65	1924	8.42
1906	8.58	1925	8.62
1907	8.66	1926	8.63
1908	8.43	1927	8.60
1909	8.53	1928	8.58
1910	8.42	1929	8.55
1911	8.61	1930	8.72
1912	8.49	1931	8.62
1913	8.51	1932	8.68
1914	8.81	1933	8.52
1915	8.69	1934	8.63
1916	8.52		

It is probable that hereafter any large earthquake would affect at least one of the lines of the national leveling net. After the detailed leveling has been run within the 25-mile meshes to furnish the basis

for topographic maps and other engineering activities, there will be practically no place in this country, except in certain mountain areas, where a point will be more than approximately 3 miles from a bench mark whose elevation will be known. Therefore, even small areas, affected by earthquakes or suspected of being subject to tectonic changes, can be readily tested by re-running the fundamental or subsidiary lines of levels in the vicinity to determine what movements have occurred.

While rather crude leveling might be good enough to furnish control for contouring topographic maps, yet it is believed that because of the many more precise uses for leveling data in other activities of our people, the detailed work within the 25-mile meshes should be of quite high grade—probably up to second-order accuracy. Leveling of this type can be run at a cost almost as low as leveling of less accuracy. Even the supplementary leveling should be of such a quality as to be of value in stability studies.

MAGNETIC ANOMALIES AND GEOLOGIC STRUCTURES OF THE CAROLINA COASTAL PLAIN

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ABSTRACT

Reconnaissance magnetometer work on the Carolina Coastal Plain has shown that several striking anomalies exist in that region, and that many of these anomalies may be correlated with the structural features of the basement rocks. Northeast-southwest structural trends have been observed, further evidence in favor of a northwest-southeast upwarp in the neighborhood of Wilmington has been obtained, and a concealed Triassic basin has been partially outlined.

INTRODUCTION

During the past three years the writer, with the assistance at various times of William F. Prouty, J. A. Alexander, W. R. Johnson, and H. W. Straley, III, has been undertaking a magnetic reconnaissance of the Carolina Coastal Plain and adjacent portions of the Piedmont.[1] Financial assistance was obtained from the Rockefeller Fund for Research in Pure Science. This work is far from completion, but lack of funds has rendered further progress impossible for the present; hence it seems desirable to present a brief review of what has been accomplished so far.

The basement rocks.—At the Fall Zone the pre-Mesozoic rocks have a general easterly slope, and disappear eastward under a cover of younger sediments. Very little is known of the structure and composition of these "Piedmont" basement rocks, since they have been encountered in only a few deep wells. At Havelock, N.C., about 19 miles northwest of Beaufort, granite has been reported from a deep well at a depth of 2,318 feet. At Wilmington, N.C., it was found at a depth of 1,109 feet, and at Fort Caswell (mouth of the Cape Fear) at a depth of 1,540 feet. Apparently no other wells deep enough to

[1] G. R. MacCarthy, W. F. Prouty, and J. A. Alexander, "Some Magnetometer Observations in the Coastal Plain Area of South Carolina," *Jour. Elisha Mitchell Sci. Soc.*, Vol. XLIX, No. 1 (1933), pp. 20–21; MacCarthy and Alexander, "What Lies under the Coastal Plain?" *ibid.*, Vol. XL, No. 1 (1934), p. 50; W. R. Johnson and H. W. Straley, III, "An Attempt To Locate the Boundaries of the Durham Triassic Basin with a Magnetometer," *Trans. Amer. Geophysical Union* (1935), pp. 176–81.

strike the basement rocks have been drilled in extreme eastern North Carolina. The nearest wells to have done so are the 2,450-foot well at Summerville, S.C. (about 25 miles northwest of Charleston), and the 2,243-foot well at Fort Monroe, Va.[2] At Florence, S.C., a deep well reached Triassic sediments at a depth of 608 feet and ended in "trap" at 1,335 feet, showing that there is at least one Triassic basin like those of the Piedmont area entirely concealed beneath the sediments of the Coastal Plain.[3] Farther south, gravity stations of the United States Coast and Geodetic Survey indicate that in Florida there probably exists a faulted or folded zone which, in the words of Thom, is "comparable to that of the Appalachians."[4]

An examination of the isogonic map accompanying "Magnetic Declination in North Carolina in 1930"[5] discloses some evidence of magnetically disturbed areas with a general northeast-southwest trend, although the stations are too few to permit much generalization.

Thus, while there is very little published evidence, what there is indicates that the basement rocks of the Carolina Coastal Plain are similar to those exposed west of the Fall Zone and, like them, possess a general northeast-southwest trend.

Magnetic observations.—Until recently, the only magnetic observations which have been published for this area were obtained at a few stations established by the Coast and Geodetic Survey, mainly at county seats. At these stations the inclination, declination, and the horizontal intensity of the earth's field have been determined. An examination of the data shows that the declination changes in a highly irregular manner, so that only extremely generalized isogonic lines can be drawn.[6] For example, at Smithfield, N.C., declination

[2] Wendell C. Manfield, "An Oil-Prospecting Well near Havelock, N.C.," *N.C. Dept. Conserv. and Devel., Econ. Paper No. 58* (1927).

[3] N. H. Darton, "Artesian Wells on the Atlantic Coast," *U.S. Geol. Surv. Bull. 138* (1896), p. 218. A local driller has told the writer that one of his wells encountered a shale "which looked very much like the Cumnock" (middle Newark) at a depth of about 200 feet on the southern edge of the city of Florence, S.C.

[4] W. T. Thom, Jr., "Gravity Observations and Basement Structure," *Geol. Soc. Amer. Proc. for 1933* (1934), p. 117. Data furnished the writer by Dr. William Bowie of the Coast and Geodetic Survey certainly suggest that such is the case.

[5] *U.S. Coast and Geodet. Surv. Serial Publ. 537* (1932). [6] *Ibid.*

values of 2.3°, 3.5°, and 3.7° W. have been recorded while, according to the isogonic chart, the declination is about 3.5° W. Similar, but perhaps less extreme, variations in the course of a few hundred yards or even feet are recorded from many other magnetic stations in this general area. These local variations indicate the presence of local disturbances, some of which are man-made, but most of which are caused by variations in the underlying soil and rocks.

In the work done by the present writer and his associates, the instrument used was the ordinary Askania field balance, which responds only to the vertical component of the earth's field. No attempt was made to secure absolute values, but the reading obtained at Myrtle Beach, S.C., was chosen as an arbitrary datum, and all other readings referred to this. The traverses which have been run in South Carolina and southeastern North Carolina by, or under the direction of, the writer are shown in Figure 1. Some work has also been done in extreme northeastern North Carolina, but does not appear on this map.

MAGNETIC ANOMALIES

Regions of abnormally high and abnormally low readings were found at various places. The magnetic "highs" are apparently of two different types—"point" highs and "linear" highs. The former are restricted areas, usually only a few hundred yards across, in which the magnetometer readings are well above the regional average. It has been found that point highs are almost invariably associated with the elliptical bays that dot the Carolina Coastal Plain, but the reverse relation—i.e., that there is a bay associated with each point high—has not been proved as yet.[7]

The linear highs consist of elongated areas of abnormally high readings and occur both single and in parallel or sub-parallel groups. Readings taken along the axes of such highs are well above the regional average, but drop off sharply along lines normal to the axes. Every one of these linear highs so far investigated shows a general northeast-southwest trend, and hence parallels roughly the general structural trends of the Piedmont and Appalachian regions. A few of these linear highs are shown in Figure 1.

[7] W. F. Prouty, "'Carolina Bays' and Elliptical Lake Basins," *Jour. Geol.*, Vol. XLIII, No. 2 (1935), pp. 200–207.

Origin of the linear highs.—Since any magnetic high signifies the presence of material of relatively high magnetic susceptibility, it appears that there must exist a series of linear masses of such (ferruginous) material to account for the observed highs. There is nothing in the surficial geology of the region to indicate the presence of such material; therefore, it seems evident that it must be present

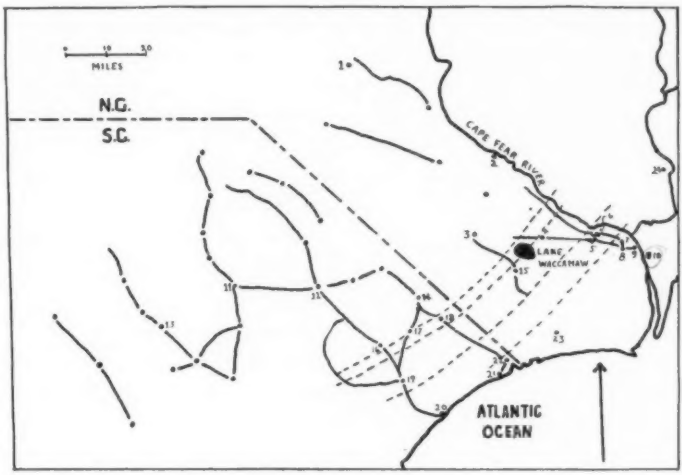

FIG. 1.—Sketch map, showing the position of the traverses, the location of the towns mentioned, and the position of the trend lines deduced from the magnetic observations. Traverses are solid lines, trend lines are dashed. Towns: 1. Raeford; 2. Elizabethtown; 3. Whiteville; 4. Bolton; 5. Delco; 6. Acme; 7. Phoenix; 8. Leland; 9. Navassa; 10. Wilmington; 11. Florence; 12. Marion; 13. Lynchburg; 14. Green Sea; 15. Old Dock; 16. Cool Springs; 17. Bayboro; 18. Loris; 19. Conway; 20. Myrtle Beach; 21. Cherry Grove Beach; 22. Little River; 23. Shallotte; 24. Burgaw.

either in the deeper horizons of the Coastal Plain or in the underlying basement rocks.

The first supposition reduces to this: that during the accumulation of the sediments long, narrow streaks of magnetic "pay-sands" were segregated along the beaches which were, unfortunately enough, roughly parallel to the structural trends of the Piedmont and Appalachian regions. Such accumulations are known on modern beaches, and their possible occurrence in the Coastal Plain sediments

must be considered, but the symmetrical relations of many of the highs and their magnitudes seem to rule out this explanation.

The second supposition involves the presence of deep-seated iron-bearing formations in the basement rocks. Such iron-rich masses might be sheet-like deposits of iron ore, dikes of iron-rich intrusives, or, less probably, buried ridges of crystalline rock. The magnitude of some of the anomalies renders the last alternative highly improbable. Haalck[8] gives 200 gammas as the upper limit for anomalies in ordinary sedimentaries, 100 to 1,000 gammas as the usual range in large masses of iron-poor volcanic and crystalline rocks, and 1,000 to 10,000 gammas as the usual range in large masses of iron-rich igneous rocks. The anomalies encountered on the Carolina Coastal Plain range upward to 2,000 gammas or more, and hence would fall in Haalck's class of large masses of iron-rich volcanic and crystalline rocks. When one considers that in many places the basement rocks lie at depths of 2,000 feet or more, the existence of anomalies of this order of magnitude implies the presence of a very considerable amount of highly susceptible material.

The distribution of the linear anomalies.—While many anomalies have been observed in the area investigated, the most interesting region appears to be a greatly disturbed zone not far from and roughly parallel to the coast. It was encountered first near Cool Springs, S.C., on the Conway–Marion highway (Fig. 1) where it occurred as a double-crested high. The higher peak rose about 1,200 gammas and the other about 700 gammas above the average of the vicinity. The crest or axis of the higher peak was followed for about 1,000 feet to the west and for about 1,300 feet to the east, where a large swamp rendered further progress impossible. In this distance the readings rose 600 gammas more, to a total of about 1,800 gammas above those of the surrounding area. A sub-parallel traverse along the Conway–Green Sea highway disclosed a high of 700 gammas near the village of Bayboro. Since this high was not investigated in detail, its maximum value and shape is as yet unknown. A third traverse along the Green Sea–Little River highway disclosed a magnetic high just southeast of the town of Loris. Here several readings were taken at

[8] Quoted by A. Broughton-Edge and T. H. Laby in *The Principles and Practice of Geophysical Prospecting* (Cambridge: University Press, 1931), p. 178.

quarter-mile intervals, with the highest reading rising about 600 gammas above the regional value.

Still farther to the northeast a disturbed area seems to exist along the North Carolina–South Carolina border approximately 19 miles from the coast.[9] The disturbed zone was next picked up on the Whiteville–Shallotte road where, near the village of Old Dock, a

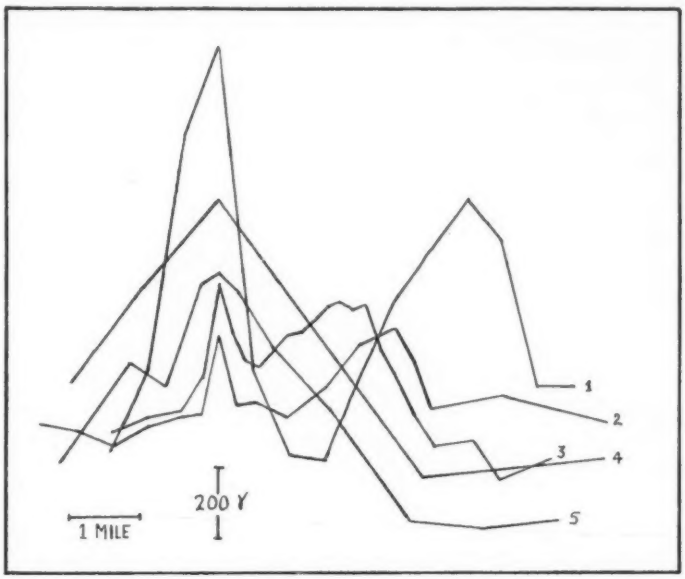

FIG. 2.—Comparative magnitudes of some of the anomalies described in the text. 1. Cool Springs; 2. Old Dock; 3. Bolton; 4. Bayboro; 5. Loris.

small but distinct, double-crested high was encountered. The maximum reading was only about 275 gammas above the regional average, but again the intervals were so great that there is no assurance that the highest points were not missed.

Readings of about 450 gammas above the regional average were obtained just west of Bolton on the Wilmington–Whiteville high-

[9] Here a party engaged in a re-survey of the state boundary encountered a local variation in their compass of 20 minutes or more. (Personal communication.)

way, and a similar anomaly of about 400 gammas was found about 9 miles from Delco along the Delco–Elizabethtown highway.

Since none of the individual highs were traced very far along their axes, it is entirely possible that no continuous highs exist, but it seems extremely probable that a line drawn between the points mentioned above would lie near the axis of a continuous linear high.

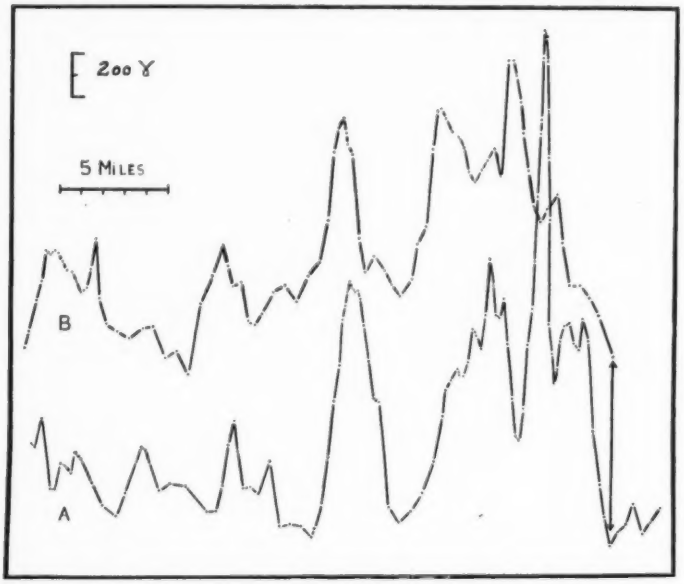

FIG. 3.—Magnetometer traverses along the Elizabethtown–Acme–Leland-Navassa and the Whiteville–Bolton-Leland roads. *A* is the Acme traverse, *B* the Bolton traverse. In drawing the figure, traverse *B* has been raised 900 gammas above its true value. Leland, which is the only point common to the two traverses, is indicated by the arrow.

This interpretation of the data is rendered more probable when other investigations (described below) are considered. In this connection it should perhaps be mentioned that an extremely sharp-crested linear high with a northeast-southwest trend was traced along its axis for over a mile at a point about 3 miles north of Elizabethtown. This high is not shown on the map. The comparative magnitudes of the various highs described above are shown in Figure 2.

The Wilmington highs.—Good evidence that these highs are actually linear was obtained between Bolton and Wilmington, between Delco and Elizabethtown, and along the Acme–Phoenix–Leland road (Fig. 3). In this figure the horizontal distances are not those actually measured along these roads, but have been corrected for road curvature by plotting the readings as projected along the straight line *AB* of Figure 4. The most striking thing about these sub-parallel traverses is their great similarity. Obviously, the same set of highs has been cut by each of the traverses. Equally striking is the almost

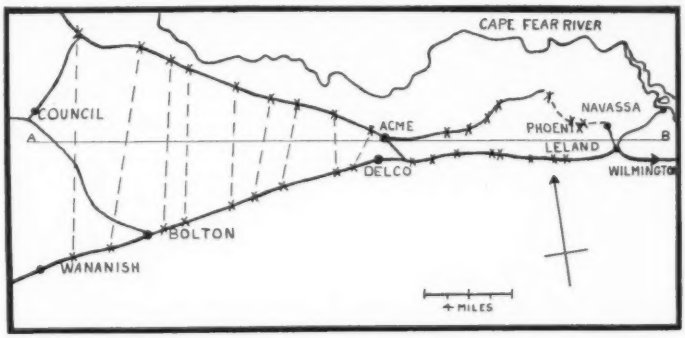

FIG. 4.—Sketch map of the roads in the vicinity of Navassa, Acme, Delco, Bolton, etc. The position of some of the highs mentioned in the text is shown. Dashed lines are trend lines obtained by connecting corresponding crests and troughs.

cyclic regularity which the highs exhibit, each series running through a group of five minor peaks before culminating in a main crest. On the map (Fig. 4) the corresponding crests and troughs west of Delco have been connected by dashed lines. This has not yet been attempted east of Delco, since the only available map of the Acme–Phoenix–Leland road is in considerable error, and no opportunity to correct it has as yet presented itself.

The cyclic regularity of these highs, together with their sub-parallel arrangement, suggests a highly ferruginous bed (or other sheetlike mass; perhaps a dike) or a series of such beds, which has been thrown into a series of folds whose trend is about N. 35° E. The "herringbone" pattern which they assume further suggests that they are gently plunging folds. The plunging character of these suggested

folds should be expected if the Wilmington anticline (discussed below) is taken into consideration. The general strike of these highs would place them nearly parallel to, but southeast of, the group of highs west of Bolton. They therefore would lie to the east of Cherry Grove Beach and hence on the seaward side of the strand, so that they would not be encountered either at Cherry Grove or at Myrtle Beach. A single reading taken on the outskirts of Burgaw indicates the presence of at least one high in that neighborhood and, as the map (Fig. 1) shows, Burgaw lies approximately along the strike of the first high west of Delco.

A traverse in extreme northeastern North Carolina, just completed by W. R. Johnson, shows two highs in the vicinity of Columbia, which seem to lie somewhere near the projected strike of the Leland-Delco group. The distance (170 miles) is too great for even a tentative correlation, but the data are at least suggestive.

The Wilmington anticline.—Stevenson[10] has suggested that the course of the Cape Fear River across the Coastal Plain approximately marks the axis of a broad structural uplift dating from the end of the Cretaceous. He places the axis of this uplift parallel to, but slightly to the south of, the river. Mansfield[11] notes that the depths at which granite was encountered in the wells at Havelock, N.C., Wilmington, N.C., and Summerville, S.C., support this view. He says, in substance, that these three wells are in an approximately straight line trending about N. 56° E. and roughly parallel both to the present coast and to the line marking the inner edge of the Coastal Plain (the Fall Zone). Wilmington is some 150 miles from Summerville and about 65 miles from Havelock. The logs of these three wells (Havelock: granite at 2,318 feet; Wilmington: granite at 1,109 feet; Summerville: granite at 2,450 feet) indicate that the surface of the basement rocks at Wilmington lies about 1,200 feet higher than it should on the assumption of a uniform dip of this surface. Leland must lie not far from the crest of this uplift, here called the Wilmington anticline.

On the map (Fig. 1) the structural trends obtained by connecting

[10] L. W. Stevenson, "Major Features in the Geology of the Atlantic and Gulf Coastal Plain," *Jour. Wash. Acad. Sci.*, Vol. XVI, No. 17 (1926), pp. 260–480.

[11] *Op. cit.*, p. 11.

corresponding crests and troughs seem to swing around in a gentle curve just as they should if they are due to structures involved in this uplift which, by the evidence of the Fort Caswell well, probably plunges to the southeast. Moreover, if the crest of this anticline does pass close to Leland, the increasing uplift of the basement rocks as the crest is approached would account for the increasing magnitudes from west to east of the successive peaks shown in Figure 3. Also, the greater size of the anomalies in the Wilmington region compared with the size of those due to what appears to be the same structure in the Loris and Old Dock vicinity may be accounted for by assuming that the latter regions lie over relatively depressed areas of the basement rocks, and well to the west of the axis of uplift. While none of these suggestions can be regarded as proved, they form a coherent picture and account for the known facts, both geological and geophysical.

Other results.—As a result of the traverses made to the northeast and southwest of Florence (Fig. 1), the Triassic basin, hitherto known only from the log of the deep well at Florence, has been traced from near Lynchburg, S.C., northeast to the vicinity of Raeford, N.C. Some evidence has also been obtained that the slope of the surface of the basement crystallines suffers a rather abrupt change along a line roughly parallel to the present coast, but some 25 miles inland. These results will be presented in greater detail in later papers.[12]

SUMMARY AND SUGGESTIONS

1. A magnetically disturbed zone, roughly parallel to the coast, and consisting of a series of sub-parallel highs and lows, has been found. This zone has been traced from the vicinity of Myrtle Beach to the vicinity of Wilmington, with further evidence suggesting that it may continue through Burgaw toward extreme northeastern North Carolina. The trend of this disturbed zone roughly parallels the structure trends of the Piedmont and Appalachian districts, and it is highly probable that it represents a folded and perhaps fractured zone such as is indicated by the gravimetric work of the United States Coast and Geodetic Survey in Florida.

[12] Brief abstracts have appeared in the *Jour. Elisha Mitchell Sci. Soc.*, Vol. XLIX, No. 1 (1933) pp. 20–21, and Vol. L, No. 1 (1934), p. 50.

2. Evidence supporting Stevenson's suggestion of a northwest-southeast structural uplift near Wilmington has been obtained.

3. A Triassic basin, hitherto known only from the log of a deep well, has been traced for a considerable distance northeast and southwest of Florence.

4. Some evidence has been obtained of an abrupt change in the slope of the basement crystalline along a line inland from, and roughly parallel to, the coast.

5. Further magnetic work in this area is urgently needed.

6. If a net of gravimetric stations, similar to that established by the Coast and Geodetic Survey in Florida, were available in the Carolina Coastal Plain, correlation between magnetic and gravimetric data would be possible. The data obtained by each method would supplement and aid in the interpretation of those obtained by the other and by the more usual geological methods.

PRIMARY BANDING IN BASIC PLUTONIC ROCKS

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ABSTRACT

The nature and suggested modes of origin of the mineralogically unlike bands so frequently observed in bodies of basic plutonic rock are reviewed. A mechanism for the production of some of these bands is suggested, involving simultaneous crystallization and settling of two or more minerals in a magma lighter than any of them. By a process of *rhythmic differential settling*, rhythmically alternating bands of differing composition may be produced. The same process may account for anorthosite bodies without necessitating the assumption of the crystallization of plagioclase from a liquid heavier than itself, provided only that the plagioclase be lighter than the mean specific gravity of liquid and heavy minerals together. Experimental evidence is adduced in support of the suggested mechanism.

INTRODUCTION

In many parts of the world, basic plutonic rocks, especially gabbros and norites, have been observed to display a banding, due to the alternation of mineralogically unlike layers. To explain this banding, numerous explanations have been put forward, many of which involve either deformation or change of physico-chemical conditions during crystallization. The writer wishes to suggest for some of these occurrences a possible explanation which involves neither an elaborate mechanism nor rapid changes in physico-chemical conditions.

The writer wishes to express his indebtedness to Dr. Howel Williams for helpful discussion and constructive criticism, and to Dr. R. A. Bramkamp for the photograph, Figure 1.

DESCRIPTION OF THE PHENOMENA

In the Duluth gabbro,[1] mineralogically unlike layers or flat lenses may show minor undulations or bunches; rarely do they curve or finger into each other. There are no transverse dikes or connections, but the layers may branch and split.

In the kakortokites of Greenland, Ussing[2] has recognized a well-

[1] F. F. Grout, "Internal Structures of Igneous Rocks," *Jour. Geol.*, Vol. XXVI (1918), pp. 441–44.

[2] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Med. om Grønland*, Vol. XXXVIII (1911), p. 43.

developed banding, nearly horizontal throughout, but showing slight undulations. The sheets are of variable thickness, and the banding disappears near the intrusive contact with the older rocks.

Adams[3] has described small-scale, vertical banding in volcanic plugs in the Monteregian Hills, due to the alternation of mineralogically unlike layers, already differentiated before the magma reached its present position.

Harker,[4] in describing the banded gabbros of Skye, writes of patches and streaks, clearly referable either to separation in place or to inhomogeneity at the time of intrusion. The bands may wind and pucker considerably. Whether or not he believed the magma to have had any quantity of suspended crystals in it at the time of intrusion is not quite clear.

In discussing the same occurrence, Geikie and Teall, as quoted by Harker,[5] write of alternating light and dark bands, varying in thickness from a foot downward, with thin black seams, rich in titaniferous iron ores. Adjoining bands may in some cases grade into each other, or be sharply bounded. Crystals interlock at the boundaries between the bands.

On the Isle of Rum, according to Harker, is a complex of rocks rich in olivine and basic plagioclase, each individual sheet of the complex being heterogeneous, consisting of more peridotitic and more feldspathic portions drawn out in conspicuous bands. This arrangement is interesting in the light of Bowen's thesis[6] that rocks rich in olivine and basic plagioclase can originate only by the accumulation of both constituents as crystals.

Hall has well described the banding in the Bushveld complex. He distinguishes the local banding, on a more or less hand-specimen scale, from the regional banding, by which is meant the large-scale repetition at different horizons of thick sheets or lenses of highly specialized differentiates.

[3] F. D. Adams, "The Monteregian Hills," *Jour. Geol.*, Vol. XI (1903), p. 281.

[4] A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv. Great Britain* (1904), pp. 90–92.

[5] *The Natural History of Igneous Rocks*, New York: Macmillan Co., 1909, pp. 138–40.

[6] N. L. Bowen, *The Evolution of the Igneous Rocks* (Princeton University Press, 1928), pp. 164–65.

The former is found at many points throughout the entire zone, but met with rather more abundantly in the lower portion, and is expressed in a banded appearance of the rocks, due to which they are streaked in layers of different mineralogical composition. The latter range in thickness from a few inches down to a small fraction of an inch, and in many cases darker layers—much richer in pyroxene, etc., than normal massive norite—alternate with light-colored ones rich in plagioclase. The banded anorthosites of the "critical level" afford very fine examples e.g., in northern Sekukuniland. Split along a plane of banding the minerals of a layer (e.g. bronzite) are seen to lie in all azimuths within that plane, but on cross-fracture the tabular habit gives rise to an approximately linear disposition in the direction of the longer edges, comparable to the sub-parallel arrangement of a large number of closely packed logs of wood floating down a stream.[7]

According to Wagner's[8] description of the same phenomenon, this orientation is found in both prismoid and tabular crystals, and the structure has been termed by Bowen a sedimentation phenomenon.

Grout[9] has described similar orientation in the Duluth gabbro, but has attributed it to fluxion. As nearly as can be ascertained from his Figure 8, the feldspars which reveal the "fluxion structure" are tabular rather than prismoid, nor is any linear structure to be seen. Harker,[10] in describing the rocks of Skye, says that the parallelism of feldspars is reported only locally and is the result of flow.

SUMMARY OF CHARACTERS OF BANDING IN BASIC PLUTONIC ROCKS

In many bodies of basic plutonic rocks there is a banding due to the alternation of mineralogically unlike layers. This banding may have any attitude, but is commonly parallel to the contacts. The thickness of the bands may vary from a fraction of an inch up to many feet, and the contacts between them may be gradational or sharp. Many bands split or show local distortion and variation in thickness. In some intrusions platy crystals are arranged parallel to the banding. Textures of adjacent bands differ very little, and crystals usually interlock across the contacts. Protoclastic structure is rare.

[7] A. L. Hall, "The Bushveld Igneous Complex," *Geol. Surv. So. Africa Mem. 28*, pp. 266–67.

[8] P. A. Wagner, "On the Magmatic Nickel Deposits of the Bushveld Complex in the Rustenburg District, Transvaal," *Geol. Surv. So. Africa Mem. 21* (1924), pp. 80–81.

[9] *Op. cit.*, pp. 446–48.

[10] "Tertiary Igneous Rocks of Skye," *loc. cit.*, p. 119.

PREVIOUSLY SUGGESTED MODES OF ORIGIN OF THE BANDING

Grout[11] has given a valuable summary of the possible causes of igneous banding. The first two of these, partial assimilation of inclusions and lit-par-lit injection, he dismisses summarily as lacking field evidence. "Streaked differentiation, with reference to rhythmic cooling or intrusive action" is dismissed, because none of the theories of differentiation outlines a process that will result in the combination of gravitative arrangement, parallel banding, and parallelism of grain. He believes that the orientation of the tabular crystals is necessarily a fluxion rather than a sedimentation structure, and hence that there must have been movement. The possible modes of origin of the banding are therefore limited to successive intrusion, heterogeneous intrusion, and deformation during crystallization. Successive intrusion on a small scale and repeated many times is difficult to imagine. Heterogeneous intrusion is excluded because of the stirring which would result in a large magma chamber, because crystallization differentiation would result in the destruction of banding arising from heterogeneous intrusion, because the composition of some bands is too extreme for them to have resulted from filter-pressing, and because the relative volumes of the phases resulting from two liquids imperfectly mixed are not those which are seen in the field. Grout favors convection currents, but finds it necessary to call in "rhythmic effects in the way of cooling, intrusive action, or gas emanation," in order to explain the banded change in mineral composition.

Bowen[12] has criticized the assumption of rhythmic crystallization with plagioclase and augite alternating, and has suggested that the banding results from deformation of a crystallizing mass in which crystal accumulation is occurring. He supposes an "intrusion of the more completely liquid portion into rifts in the crystal mesh of the part of the mass in which the proportion of crystals is much greater." Diffusion may be operative in producing drastic differentiation effects. The principal difficulty with this hypothesis seems to the writer to be the production of rifts in the crystal mesh which could approach in regularity and horizontal extent the bands observed in

[11] *Op. cit.*, pp. 452–57. [12] *Op. cit.*, pp. 168–70.

many large plutonic bodies. Further, Bowen's suggestion[13] that the basining of the floor would cause the separation of the upper layers of the crystal mesh from the lower requires the assumption of a greater rigidity in the upper portion of a mass of crystals separating out of a liquid than in the lower portion of the same mass, which is more closely compacted. His hypothesis also requires that these two portions separate along a horizontal tabular surface of discontinuity of considerable regularity. It seems to the writer much more probable that, in the event of the basining of the floor, the crystal mesh would fail by local crushing in the upper part and tensional separation along rifts normal to the floor in the lower part, rather than by shear along a neutral surface. Bowen has also criticized Grout's hypothesis of convection as being unable to accomplish anything that settling could not do as well, or better.

Bowen[14] has well emphasized that the banding of the Hebridean gabbros, at least, is a condition brought about during crystallization, and that it was not the result of intrusion of an inhomogeneous liquid, since such inhomogeneity is never found in the more quickly chilled bodies.

Harker[15] believes that the banded gabbros of Skye were intruded as a non-uniform mass, the different portions being drawn out as a result of flow movement.

Ussing[16] does not believe that the forty sets of layers in the kakortokite mass described by him can be referred to successive intrusions, since this hypothesis is incapable of explaining the arrangement of the bands and the constancy of the thickness relations. He believes it is due to recurrent crystallization dependent upon outside conditions, probably repeated variations in pressure.

Wagner[17] offers the hypothesis of intermittent cooling to account for the large-scale lenses ("regional banding" of Hall) of harzburgite and of anorthositic norite in the Bushveld complex. He believes that there could have been a rise of the isogeotherms due to spasmodic subsidence of the floor. The explanation does not seem applicable,

[13] "Crystallization Differentiation in Igneous Masses," *Jour. Geol.*, Vol. XXVII (1919), p. 418.

[14] *The Evolution of the Igneous Rocks*, pp. 169–70.

[15] *The Natural History of Igneous Rocks*, *loc. cit.*

[16] *Op. cit.*, pp. 355–60.

[17] *Op. cit.*

nor does Wagner attempt to apply it to the local banding, on a hand-specimen scale.

Hall[18] suggests for the same body a "rhythmical 'rain' of specific minerals leading to local piles of accumulation and to their subsequent rolling out through slight differential movement, but such speculations are hardly more than the mental images of a postulated mechanism."

Daly[19] has recently suggested a slow basining of the magma body, causing temperature to vary more or less rhythmically along a fixed vertical line in the liquid so disturbed, with a resultant rhythmical showering of early-formed crystals, and development of banding in depth.

SUGGESTED MECHANISM FOR THE PRODUCTION OF BANDS

The writer wishes to suggest a mechanism which he believes will account for the production of some types of banding by the differential settling of two or more crystalline phases continuously separating from a liquid, the specific gravity of which is but slightly less than that of the lightest crystalline phase, at the temperature of separation.

If two sorts of crystals of differing densities are settling in a liquid, the density of which is but slightly less than that of the lighter sort of crystal, both varieties will settle toward the bottom. As these two kinds of crystals approach the bottom, the proportion of crystals to liquid will increase. When a certain limiting value is reached, since the sinking of the heavier crystals tends to displace the adjacent fluid upward, this liquid, because of its viscosity, and the slow rate of settling of the lighter crystals, carries them upward. There is thus produced a layer rich in the lighter crystalline constituent, over one rich in the heavier. Crystals of the heavier variety, continuing to fall upon the loose mesh of the lighter crystals, will slip through the interstices of the mesh until, by the settling of the lighter crystals relative to the liquid, this mesh becomes too tight to permit the passage of any further crystals of the heavier variety. The process

[18] *Op. cit.*

[19] R. A. Daly, *Igneous Rocks and the Depths of the Earth*, New York: McGraw-Hill Book Co., 1933, p. 354.

then repeats itself, another layer of heavy crystals being formed on top of the layer of light crystals. The process may be termed *rhythmic differential settling*. Its operation depends upon the compresence of several essential factors.

1. The density of the liquid must be somewhat less than that of the lighter of the two varieties of crystals.

2. The viscosity of the liquid must be great enough to carry upward the lighter crystals, but not so great as to prevent their settling before crystallization is complete, as in many banded laccoliths.

3. The two kinds of crystals must be of approximately the same size, or one kind will slip through the crystal mesh of the other kind to a disproportionate extent.

4. The specific gravities of the two kinds of crystals must not be too close together.

FULFILMENT OF SUGGESTED CONDITIONS BY BASIC MAGMAS

The fulfilment of the first condition is most debatable and will be discussed last.

The mere existence of bodies of plutonic rock showing differentiation is evidence that the viscosity is not so great as altogether to inhibit settling. Whether the viscosity is sufficiently great to permit rising currents to carry crystals upward depends upon the velocity of settling of the crystal when no currents are present. Grout[20] suggests as the average range in the viscosity of magmas 5–300, in poises.

Common experience confirms the close approach to equidimensionality of crystals. Experience also shows that the specific gravity differences between the minerals are sufficient for gravitative differentiation.

The relative specific gravity of molten gabbro or norite and the plagioclase separating from it has not yet been accurately determined, to the knowledge of the writer. Grout[21] estimates that at 1200° C. liquid gabbro has a density of 2.74, and solid Ab_1An_1 a density of 2.61. Bowen[22] estimates that the densities of molten

[20] "Two-phase Convection in Igneous Magmas," *Jour. Geol.*, Vol. XXVI (1918), p. 486.

[21] *Ibid.*, p. 489.

[22] "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXV (1917), p. 211.

gabbro and calcic plagioclase are almost identical, the crystals being a very little lighter. The experimental work upon which these estimates were based was performed on dry melts. It is possible that dissolved volatile matter may operate to decrease the specific gravity. Daly[23] thinks that plagioclase is denser than molten norite.

EXPERIMENTAL REPRODUCTION OF THE BANDED STRUCTURES

Experimental conditions.—In an endeavor to reproduce experimentally the banded structures, recourse was had to some rough experiments in which the essential physical conditions were fulfilled as far as possible.

In order to simulate as nearly as possible the specific-gravity differences which might be expected in a natural magma system, a quantity of labradorite and of hedenbergite crystals was crushed, cleaned, and sieved. Four size groupings were used: (1) from $\frac{1}{2}$ mm. to 60 mesh; (2) from 60 mesh to 80 mesh; (3) from 80 mesh to 150 mesh; and (4) minus 150 mesh. In order to eliminate the finest powder from the minus 150 mesh size, the material was settled in water for 15 seconds in the case of labradorite and 10 seconds in the case of hedenbergite, the part remaining in suspension being discarded. Specific gravities were measured on each fraction. The specific gravity of the labradorite ranges from 2.65 to 2.70, the average being about 2.68. The specific gravity of the hedenbergite ranges from 3.48 to 3.55. Amounts of each grade of mineral were weighed out proportional to its specific gravity, and the labradorite and hedenbergite of the same grade were mixed, giving mixtures of the two minerals containing approximately equal volumes of each. The particles of both minerals in each mixture were roughly of the same size, as shown by microscopic examination, though unavoidably of different shapes, because of the tendency of the labradorite to break into tabular fragments, the hedenbergite into acicular ones. The mixtures were then placed in cylindrical glass vials, containing mixtures of bromoform and alcohol, the specific gravity of which had been adjusted to such a value that particles of labradorite $\frac{1}{2}$ mm. in diameter required 3–4 seconds to sink 5 cm. This specific gravity differed from that of the labradorite by about 0.05.

[23] *Op. cit.*, p. 354.

The vials containing the bromoform and mineral mixtures were stoppered and shaken, and the minerals allowed to settle. The depth of the column of minerals was between 6 and 7 cm. for the three finer sizes, and 4 cm. for the coarser size.

During the process of settling, it was observed that differentiation was taking place to a considerable extent. The process was most easily observed in the coarsest size. The particles of pyroxene nearest the bottom settle rapidly through the suspension of plagioclase and liquid. The liquid rises relative to the pyroxene, carrying with it the plagioclase. At the same time, the concentration of both minerals increases in the bottom part of the column, relative to the top, since labradorite is sinking relative to the liquid, but rising relative to the pyroxene. Until the packing of the crystal mesh of plagioclase reaches a certain tightness, it is quite easy for pyroxene fragments to slip through the interstices between plagioclase fragments. When the packing of plagioclase reaches this limiting figure, it is no longer possible for pyroxene to penetrate the mesh, and a layer of pyroxene begins to accumulate on top of the plagioclase. The perfect development of this process would give rise to a banding of alternately plagioclase- and pyroxene-rich portions. When the settling is watched closely, however, it is observed that there are formed local segregations of plagioclase-rich liquid, which contain sufficient plagioclase to resist, as would a sieve of too fine a mesh, any tendency of pyroxene to pass through. Some of the masses of plagioclase are trapped at various levels by the mass of overlying minerals having become too dense to allow penetration. Other masses of labradorite are carried upward, perhaps because of local convection currents in the liquid, and may break through to the surface of the mixed column. The final result is a mass which is partially stratified on the basis of specific gravity, but stratified in a rudely rhythmic fashion. At the bottom is a zone in which the two minerals are mixed intimately. This may be a centimeter deep, and grades upward into a zone of increasingly distinct stratification which, however, is far from perfect. On top is a zone of plagioclase free from pyroxene, 4 or 5 mm. deep.

The bands of labradorite in the second zone vary in width from 1 to 3 mm., are not by any means horizontal, but branch and anas-

tomose, pinch and swell. The boundaries are rather indefinite, but banding increases in clarity of definition toward the top of the column. It is probable that in a larger vessel, protected from convection currents, the banding would be more regular.

FIG. 1.—Photograph, approximately natural size, showing banding developed by shaking and allowing to settle a mixture of equal volumes of labradorite and pyroxene, in diluted bromoform. Note increasing thickness and sharpness of definition of light bands toward the top, also the upper layer of pure feldspar.

A typical example of the banding produced by shaking the coarsest size and allowing it to settle is shown in Figure 1. The lighter bands are rich in labradorite; the darker, in pyroxene.

In all experiments it was noted that a certain amount of liquid was necessary to bring into suspension a given weight of mineral of a given size. If less than this amount is used, part of the mineral cakes in the bottom, remaining so on shaking. An addition of liquid much beyond that necessary to bring into suspension all the mineral particles does not increase the number or perfection of the bands, but does increase the perfection of the separation of the uppermost band of plagioclase. This band was present in all experiments, and of considerable width, varying from 5 mm. to 30 mm., with almost no admixture of pyroxene.

In another experiment, made to determine the effect of varying the proportion of mineral to liquid, it was found that if, after settling, the ratio of the height of the mineral column to the total height of the liquid and mineral column were less than 1:2, little or no banding had been developed, save that the plagioclase was completely separated from the pyroxene.

The finer grades showed slight banding only, the banding being obscured by the weak color contrast between the two constituents.

Effect of decreasing specific gravity of liquid.—A second series of experiments was made to determine the effect of gradually reducing the specific gravity of the liquid, by the addition of alcohol, the initial specific gravity at room temperature being 2.628.

Dilution at first had no effect, but ultimately decreased the number of bands and the sharpness of their definition to the point at which they could no longer be seen. Even at this stage, however, the column was still divided into two parts, the lower one rich in pyroxene, the upper pure plagioclase. The comments made earlier about the irregularity of the stratification are here equally applicable. The irregularity is due in part, especially in the finer sizes, to the rising of bubbles through the mass, disturbing the stratification. There is a tendency, especially noticeable in the coarsest size, for the lower part to be most nearly homogeneous, the lowermost observable layers to be thinnest and least sharply bounded; many of the higher layers were thicker, more sharply bounded, and more irregular. The finest size showed two layers only, whatever the density of the liquid.

Effect of varying specific gravities of solid phases.—In order to determine the effect of increasing the specific gravity differences between the two solid phases, further experiments were made, using plagioclase and pyroxene in one vial and ilmenite and quartz in another. The ilmenite-quartz mixture was minus 40 plus 60 mesh, and contained approximately equal volumes of ilmenite and quartz. In each vial the specific gravities of the liquid used were adjusted so that a $\frac{1}{2}$-mm. fragment of the lighter mineral required 5 seconds to sink 8 cm.

The dry mixtures were poured in a continuous stream into the liquids. When settling was complete the vial containing the plagioclase-pyroxene mixture showed an upper band 9 mm. thick, a lower one 46 mm. thick, with a number of irregular and discontinuous bands of feldspar in the lower portion.

The vial containing the quartz and ilmenite mixture showed, after settling was complete, a total height of mineral and liquid of 68 mm., the mineral column making up 50 mm. of this. The lower 40 mm. of the mineral column showed alternate bands of ilmenite and quartz, up to seven in number. The layers were more regular than with the

pyroxene and plagioclase mixture, but also tend to lens out and branch. The regularity of the banding was decreased by the turbulence of the liquid when the grains were poured in.

Both vials were shaken and the mixtures allowed to settle. As compared with the results obtained by pouring the mixture into the liquid, the thickness of the uppermost or light-mineral zone was diminished, and the regularity and thickness of bands in the mixed zone were increased. The crowding together of fragments is much greater when the whole bulk is shaken up than when the fragments are poured into the liquid. In the latter case the zone of crowding, where the lighter fragments are buoyed up by the sinking of the heavier ones, is probably much thinner at any one time. Nevertheless, it is interesting to note that banding can be produced by this mode of addition of fragments to liquid, as well as by dispersing the whole mass of fragments through a relatively small quantity of liquid. In both experiments the boundaries between the quartz and ilmenite layers are better defined than those between feldspar and pyroxene, probably because the two former show less overlap in settling rates as compared with plagioclase and pyroxene fragments of varying size in liquids of comparatively low specific gravity. It seems probable, then, that the greater the difference in specific gravity between the two minerals, the greater is the allowable difference between the specific gravity of the lighter minerals and that of the liquid.

Relative effects of size and viscosity.—It may be objected that the use of so fluid a liquid as bromoform is unjustified in attempts to reproduce settling conditions in natural magma systems; or that the fragments involved are much smaller than the crystals in the basic plutonic rocks in question. It is believed that these two departures from the ideal tend to balance each other. A consideration of Stokes's law for the settling of small spheres in a viscous medium shows that the velocity of fall $x=\frac{2gR^2\ (d-d_1)}{9V}$ where R is the radius of the sphere, d the density, d_1 the density of the fluid, g the acceleration of gravity, and V the viscosity in poises. The velocity of fall is then directly proportional to the square of the radius and inversely proportional to the viscosity of the fluid. We have already seen that

Grout estimates the viscosity of natural magmas at from 5 to 300 poises. The viscosity of bromoform at 10° C. is 0.02217. The ratio of the assumed viscosity of magma to that of bromoform varies from 215 to 12900. The average size of the particles which showed any banding in the present experiments was from 0.5 to 0.015 mm. Assuming the highest viscosity for magmas, 300 poises, particles having equal specific gravity differences and ranging in diameter from 57 mm. to 1.7 mm. should be expected to show banding. Assuming the lowest viscosity estimated by Grout, 5 poises, particles ranging in size from 7.3 to 0.22 mm. should show banding produced in the manner outlined above. Over the whole range, then, crystals of the sizes commonly observed in basic plutonic rocks should be capable of settling in the manner suggested. The factors of lowered viscosity and decreased crystal size thus tend to balance each other.

REVIEWS

"On Several Archäan Rocks from the South Coast of Norway, II: The South Norwegian Hyperites and Their Metamorphism," by W. C. BRØGGER, in *Skr. Norske Videnskaps Akad., Oslo, Math.-Naturvid. Kl.*, No. 1 (1934). Oslo: Jacob Dybwad, 1935. Pp. 421; figs. 148; map 1.

The peculiar gabbro-rocks, first described by A. Erdmann and J. H. af Forselles as "*hyperites*," from Vermland and other regions of Sweden, were thoroughly investigated by A. E. Törnebohm already in 1877. . . . . Numerous occurrences of different varieties of such hyperites (in a larger sense) are scattered within a broad zone along the eastern boundary of "the south-western gneiss-area" of Sweden.

Thus Brøgger begins his memoir on the south Norwegian hyperites, but nowhere does he give a definition of what he means by hyperites, although he says:

Macroscopically the typical hyperites of the Kragerø region are commonly of a dark brownish-violet colour, medium-grained, more seldom coarse-grained or fine-grained, with "ophitic" structure owing to the lath-form of the predominant mineral, a basic plagioclase (mostly labradorite). They are further mostly composed as *olivinehyperites*, with a rather considerable content of *olivine* together with *plagioclase* and *monoclinic pyroxene* as the main original minerals; *rhombic pyroxene* (hypersthene or bronzite) is only scarce as original, primary, mineral, except in varieties shading into norites; *biotite* is not rare, and occurs sometimes in rather considerable amount; *iron-ore* (ilmenite with magnetite) is always present, *pyrite* more accessoric; *apatite* occurs, but in the original altered rock is usually only scarce; *pleonaste* in minute grains is not very rare, the grains are commonly enclosed within the ilmenite. Other minerals . . . . occur mostly not as original, primary constituents, but in the "coronas" only, and in later stages of metamorphism . . . . , or they are fully accessoric.

So far as the description goes, the rocks appear to be gabbros and olivine-gabbros with accessory hypersthene, but since the first one hundred pages of the memoir are devoted to a discussion of coronas in these rocks, it would appear that Brøgger would make coronation essential to the definition. Since the term "hyperite" comes from hypersthene, it would seem that that mineral should be present in more than accessory amounts to justify the name. In fact, in most of the older definitions, this mineral

is regarded as an essential. In the third volume of my *Petrography*, which unfortunately is not yet in print, the following history of the term is given:

Hyperite is an old Swedish name for rocks composed of hypersthene, plagioclase, and augite or diallage. It was in use as early as 1849, for in that year Naumann gave it as synonymous, in part, with diabase and diabase-porphyry. Senft used it (1857) for the name of a group which included granular rocks composed of pyroxene and labradorite or saussurite or garnet, making three divisions—eklogite, gabbro, and hypersthenite, the latter composed of labradorite and hypersthene. Zirkel (1866) used it as a synonym for hypersthenite, which he applied to the granular labradorite-hypersthene rocks which we now call norites. Törnebohm, in 1877, suggested retaining the name hyperite for those rocks to which the name had long been applied in Sweden. They contain hypersthene, usually accompanied by augite or diallage. He considered hyperite a better term than hypersthenite, since it is shorter and because hypersthene does not play such an important rôle as the latter term would seem to indicate. "Wie erwähnt, ist nämlich in den in Rede stehenden Gesteinen neben dem Hypersthene fast stets Augit oder Diallag vorhanden, und nicht selten walten diese Gesteine [Mineralien?] sogar gegen den Hypersthen vor." Olivine-bearing and olivine-free members occur, the olivine increasing as the hypersthene decreases. Eichstädt thought that the texture indicates that the rocks are related to the diabases rather than to the gabbros, but Rosenbusch grouped them with the latter rocks. In the second edition of his *Mikroskopische Physiographie* he said that they stand intermediate between the gabbros and the olivine-gabbros, but this was corrected in the third edition to read "gabbros and norites."

It would thus seem that the hyperites include the hypersthene-bearing gabbros and augite-bearing norites.

The first 98 pages of Brøgger's memoir are devoted to a general introduction, chiefly treating of coronas and coronation structures. Many examples are given, and there is a good summary of the literature—rather brief up to the work of Sederholm and more extensive thereafter. Brøgger regards coronas as due to reactions between the olivine and the surrounding plagioclase, the reaction setting in "in consequence of the lowering of the temperature, etc., during and after the solidification of the rock . . . . accompanied by transport along their contact-planes of solutions of substances also from sources other than the minerals immediately adjacent."

Brøgger also thinks that the olivine is in many cases totally replaced by a granular aggregate of orthorhombic pyroxene, the amount of replacement depending upon the stage of metamorphism of the rock. In the case, however, where the olivine is completely replaced by hypersthene, the outer zones may be garnet, the garnet apparently never

occurring except when the olivine is completely replaced. This Brøgger regards as a later stage of metamorphism than the former. Eventually the olivine and diallage disappear, the original plagioclase is greatly reduced in amount, and the rock becomes a garnetiferous hornblende-hyperite with deuteric orthorhombic pyroxene replacing the olivine. Brown hornblende, when found, he thinks is derived from the metamorphosis of diallage. Coronas of biotite around iron ore began during the magmatic stage, and there may thus be an inner zone of biotite, perhaps partially replacing the plagioclase, and an outer zone of hornblende with spinel, the latter nearly or entirely replacing the remaining plagioclase. A further stage in the metamorphism is shown by the total disappearance of olivine and pyroxene, and the occurrence of hornblende as the only ferromagnesian mineral. There is also a little garnet, and a little oligoclase and quartz at the expense of the labradorite.

In the second part of the book he deals with spotted gabbros, the transformation of hyperite to ødegårdite (a metamorphic rock derived from hyperite and characterized by scapolite as the principal salic mineral), apatite-bearing dikes, amphibolites, krageröite (not "kragerite," as incorrectly given by Watson), quartz-albitites, albitites, quartz-oligoclasites, and various carbonate dikes.

There are many new chemical analyses and calculated modes.

It is to be regretted that Brøgger has not given in this book a summary of his observations. There is a table of contents, but no index, and neither abstract nor summary.

ALBERT JOHANNSEN

Spezielle Petrographie der Eruptivgesteine: Ein Nomenklatur-Kompendium. By EHRENREICH TRÖGER. Berlin: Deutsche Mineralogische Gesellschaft, 1935. Pp. v+360. RM. 20.

For the purpose of bringing together rocks of similar composition, the rock definitions in this nomenclature compendium are grouped by similar mineralogical characteristics, instead of being listed alphabetically, although no attempt is made to give a definite system of classification. As in the reviewer's own system, Rosenbusch and Zirkel are followed as closely as possible in the arrangement, and the rocks are similarly grouped in broad classes as quartz-bearing, quartz- and feldspathoid-free, and feldspathoid-bearing. Under each class there are subdivisions based on the kind of feldspar—alkalic, alkalic plus plagioclase, plagioclase, feldspar-free.

The book is not simply a dictionary of rock-terms, however, since for each rock chemical analyses and quantative mineralogical data are given, the latter derived, where possible, from the original descriptions. In the case of innumerable new terms, very loosely defined by the original writers, Dr. Tröger has determined, either volumetrically from thin sections, or by calculation from the chemical analyses, the probable proportions, not of normative minerals, but of minerals mentioned in the original papers as present. While calculated modes are, of course, much less satisfactory than actual volumetric determinations, they do assist in clearing up otherwise meaningless definitions. It is a pleasure to see the need for a quantitative mineralogical classification being recognized more and more, and the reviewer recommends this book as indispensible to all advanced students of petrography.

ALBERT JOHANNSEN

Guidebook Ninth Annual Field Conference: The Kansas Geological Society. A. C. TROWBRIDGE, Editor-in-Chief, WALTER A. VER WIEBE, Compilation Editor. Wichita, Kan.: McCormick-Armstrong Co., 1935., Pp. 471; figs. 261. $10.

The volumes of this series are issued annually by the Kansas Geological Society to be used as road logs by the participants in the Society's field conferences. They are designed somewhat in accord with the guidebooks of the International Geological Congress, or with the guidebooks for the Western United States issued by the U.S. Geological Survey. The ninth volume outlines the route followed by last year's conference and epitomizes the geology of the upper Mississippi Valley along a selected traverse from southeastern Iowa to northeastern Minnesota.

The book is bound in flexible covers, reinforced by linen, printed after the planograph or lithoprint method and is illustrated by graphic geologic columns; line drawings; three-dimensional block diagrams; halftones; and geologic, structural, and isopachic maps. Some of the geologic maps have been reproduced in colors. The general typographic effect is pleasing.

Introducing the pages of the road log are a number of correlation charts presenting the classification of strata adopted by the leadership of the conference in contrast with other and older classifications. The log is inserted in double columns to the page with comments on the sections seen at the stops sometimes extending through two or more pages of the book. G. Marshall Kay prepared the log for the portion of the route that

lies in Iowa; J. M. Weller for Illinois; F. T. Thwaites for Wisconsin; and C. R. Stauffer, G. A. Thiel, and L. H. Powell logged the route for Minnesota. Editorial comment, revisions, and annotations to the log were made by the editor-in-chief, A. C. Trowbridge, and others.

A unique and valuable feature of the book is a series of system papers written at the invitation of the Society. The several systems encountered along the route followed by the conference, ranging from the pre-Cambrian to the Mississippian, are described by Andrew Leith, G. O. Raasch, G. Marshall Kay, A. H. Sutton, M. A. Stainbrook, and R. C. Moore. Supplemental statements on the Mississippian system in Iowa and on part of the Ordovician system in Wisconsin are presented by L. R. Laudon and C. A. Bays (with G. O. Raasch).

A further monographic aspect is given the book by a series of special papers which treat several geologic and physiographic subjects associated with the immediate field of study. C. H. Behre, Jr., writes on the Wisconsin-Illinois lead-zinc district; Arthur Bevan on the Cambrian inlier at Oregon, Illinois; and J. V. Howell on the Mississippi River arch. Further papers on stratigraphic studies come from E. H. Powers, who writes on the stratigraphy of the Prairie du Chien; from G. O. Raasch, who reviews the studies expended on the Paleozoic strata of the Baraboo area; and from G. I. Atwater, who gives a summary of the stratigraphy and structure of the Gogebic Iron Range, Michigan and Wisconsin. F. T. Thwaites summarizes some of the results of his field studies in two papers, "The Physiography of the Baraboo District" and "Zones of Mineralization of Underground Waters in Minnesota, Iowa, Illinois and Wisconsin."

The remaining pages of the volume are devoted chiefly to illustrative material. In connection with the illustrations, however, L. E. Workman contributes a discussion of the stratigraphy in the Mississippi Valley cross-section, which was constructed by H. S. McQueen, F. T. Thwaites, and L. E. Workman. A series of structural contour maps, drawn on the surfaces of selected formations, is submitted by J. V. Howell, F. T. Thwaites, A. C. Trowbridge, and D. J. Jones. Other maps include the isopachic series drawn for a number of formations, or groups, by several of the assistant state leaders for the conference. And, finally, as a general appendix to the volume, is added a set of detailed stratigraphic sections for some of the exposures that were presented in less detail in the graphic sections of the log. The measured sections deal with about forty of the scheduled fifty-six stops of the trip, and are accompanied by a number of generalized and detailed sections of outcrops not seen along the immediate route of the conference.

It takes but a cursory glance to acquaint the reader with the value of all the reference material contained in these pages extraneous to the log. Further examination will enable one to see that discussions appearing for the first time in geological literature are before him. The insertion of the supplementary articles has enabled these selected students of the geology of the upper Mississippi Valley to crystallize their ideas and to present rather summary views of their subjects. These views are not in complete accord, but space is given to the expression of both or all sides taken in debated questions. The conference has served as a forum in which the observers most interested in the field have expressed themselves. The *Guidebook* will serve as the repository of these expressions in a most serviceable way for those now interested, and, in the years to follow, for those who will become so.

JOHN R. BALL

A Survey of Road Materials and Glacial Geology of Maine. By H. WALTER LEAVITT and EDWARD H. PERKINS. Maine Technology Experiment Station, Bulletin 30. Orono, Maine: University Press. Vol. I. *A Survey of Road Materials of Maine* (1934): Part I, *Their Occurrence and Quality.* Pp. 487; figs. 39. Part II, *Maps Showing Location of Road Materials.* Pp. iii; maps 129. Vol. II, *Glacial Geology of Maine* (1935). Pp. viii+232; figs. 39; maps: "Glacial Deposits of Maine"; "Preliminary Geologic Map of Maine." $1.50.

This bulletin summarizes the results of a four-year study by several field parties. Professor Leavitt is chiefly responsible for Volume I, Part I of which contains a description of the glacial deposits in each township, with special emphasis on deposits of gravel and sand suitable for highway purposes. Tables show the percentage wear, shape, and lithologic composition of samples from each town. Volume I, Part II, contains clear reproductions on a scale of about 2 miles to 1 inch of all of the published topographic maps of Maine, and maps of territory not yet covered by topographic sheets, showing highways, drainage, and railroads. State highways and gravel deposits are printed in green.

Geologists' interest in this report will lie chiefly in Volume II, wherein Professor Perkins discusses the glacial geology of the state. Chapter i is a brief description of the various bedrock units shown on the "Preliminary Geologic Map of Maine," by Arthur Keith, which accompanies the report. Chapter ii is "Shaping of the Pre-glacial Surface"; Chapter iii discusses "Glacial Erosion." Several examples of much weathered bedrock are described, but it is pointed out that such weathering does not necessarily

antedate the last glaciation. Although glaciated valleys along the rugged coast and in the mountains are described, it is emphasized that glacial erosion had a "relatively small" part in shaping the present topography.

Chapter iv is a detailed description of glacial deposits. In addition to the till and erratics, "till terraces," topographic forms commonly assumed to be till in some of the valleys, are described. Above the lower gravel kame terraces are hummocky terraces made up of unstratified material thought to have been deposited by the ice when it had shrunk to masses within the valleys, but before lateral drainage was sufficiently established to sort the material. A discussion of forms at intermediate levels, which may have been transitional in character, was omitted. Typical till terminal moraines are "rare or lacking in Maine." Moraine-like forms are found, but these are made of stratified material and are believed to be mainly the result of irregular melting of stagnant ice.

Under the heading "Stratified Drift" the author describes moraine banks, deltas, wash plains, kame terraces, kames and eskers, and glacial clay. Kame terraces are very common in the valleys in the interior of the state and are often associated with crevasse fillings. The well-known eskers of Maine, which are equaled only by those in Finland, are described at some length. It is concluded that some of the eskers were formed in open channels and others in tunnels. Most of them are mantled by marine clay, and are, therefore, pre-marine; some, however, rest on marine clay, and thus are post-marine in age.

Chapter v is a regional description of the deposits. These may be located on the detailed maps of Volume I, Part II, and on the map of the state. Chapter vi discusses the sequence of Pleistocene events. Evidence indicates that no part of the state was left uncovered by the last ice sheet. The author believes that none of the deposits is pre-Wisconsin in age. Evidence indicates two advances of the ice, an older one from the northwest, and a younger one from the north. Both advances are Wisconsin, and probably both are late Wisconsin.

In the waning stages of ice occupancy, the ice became stagnant and melted down, as well as back, over large parts of the state. The ice of the coastal part is thought to have had a definite ice front, but away from the coast there is little evidence of a definite front. Chapter vii discusses the postglacial marine stage, and the differential uplift of the coastal region. Isobases are drawn to show the varying amount of uplift, determined mainly from deltas. Beaches are small and poor, and occur at various levels.

GEORGE W. WHITE

Geology of the Littleton and Moosilauke Quadrangles. By MARLAND P. BILLINGS. Concord, New Hampshire: State Planning and Development Commission, 1935. Pp. 51; pl. 1; maps 2. *Geology of the Franconia Quadrangle.* By MARLAND P. BILLINGS and CHARLES R. WILLIAMS. Concord, New Hampshire: State Planning and Development Commission, 1935. Pp. 35; pl. 1; map 1.

These bulletins (dealing with adjoining quadrangles) are intended for both the geologist and the layman, for whose benefit useful glossaries are added.

The exposures in the Littleton and Moosilauke quadrangles are largely metamorphosed sedimentary and volcanic rocks of Ordovician, Silurian, and early Devonian age, intersected by extensive intrusions. The only fossils thus far mentioned from New Hampshire have been found in the Moosilauke quadrangle. Their fortunate discovery has enabled the author to date the Paleozoic formations and from them, in turn, to approximate the age of the important plutonic rocks. These intrusions fall into four groups, dating from late Ordovician to post-Carboniferous in age, and were apparently related to the Taconic, the Acadian, and the Appalachian orogenic episodes.

Of interest to the structural geologist are several major folds and thrust faults. The economic geologist will find mines and quarries from which limestone, gold, granite, slate, and soapstone have been obtained.

The proportion of sedimentary rocks is smaller in the Franconia quadrangle than in the Moosilauke area adjoining it on the west. The Paleozoic schists show intense folding with concordant intrusions, the trend of which is parallel with the regional structure. Particularly interesting is the fact that several of these large intrusions show many of the characteristics of ring dikes.

H. W. STRALEY, III

"Classification and Selection of Illinois Coals," by GILBERT H. CADY in *Illinois Geological Survey Bulletin 62.* Urbana: Illinois Geological Survey, 1935. Pp. 354.

In this bulletin an attempt has been made to classify Illinois coals on the basis of the tentative specifications recently issued by the American Society for Testing Materials. In large measure, the basis of the classification is that adopted several years ago by Parr. It is, indeed, fitting that the first serious attempt to apply this classification has been made by the Illinois Geological Survey, with which organization Parr was associated for so many years.

Portions of the bulletin particularly useful to both consumer and producer are the chapter on "The Use of Grade Rating Specifications in Selecting Illinois Coals," the maps of commercially important coal beds within the state, and the appendixes, which include 274 pages of analyses of Illinois coals and nomographs for the use of the consumer in making purchases according to specifications. Both the author and the Survey are to be congratulated upon the publication of this bulletin, which should aid materially in increasing the effective and efficient utilization of Illinois' fuel resources.

H. W. STRALEY, III

Grundwasser und Quellen Kunde. By K. KEILHACK. 3d ed.; Berlin: Gebrüder Borntraeger, 1935. Pp. xi+575; figs. 308; table I.

The third edition of this well-known work on ground-water hydrology is now available. In general plan this edition follows the original. A few chapters have been omitted and several have been added. The first major division, which discusses fundamental sciences upon which ground-water hydrology is based, has not been changed materially, but the second major division, which treats of ground-water hydrology and related fields, has been enlarged. New chapters discuss geophysical methods as applied to the search for ground water. These chapters are credited to H. Reich and A. Ebert. Density, seismic, and electrical methods are discussed, but more space is devoted to the application of the resistivity method. A brief reference is made to the use of radioactivity methods. The third major division, which discusses ground-water law, refers chiefly to Germany. An innovation in this edition is the addition of a Bibliography of 248 titles, which includes a number of American references.

GEORGE M. HALL

Along the Hill. By CARROLL LANE FENTON. New York: Reynal & Hitchcock, 1935. Pp. 96; figs. 52. $1.25.

In answer to a demand for a popular guide to common geologic features observed in the field by young people and adults alike, who find tramping among rocks a new and fascinating hobby, Dr. Fenton has brought out this interesting little book. Doubtless the book will prove to be very popular among nature-study clubs, summer scout camps, and other similar organizations. Its pocket size makes the volume quite usable in the field.

DAN J. JONES